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Loading Cycles for the Fatigue Reliability Analysis of Miter Gates

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WES

Prepared for Headquarters, U.S. Army Corps of Engineers

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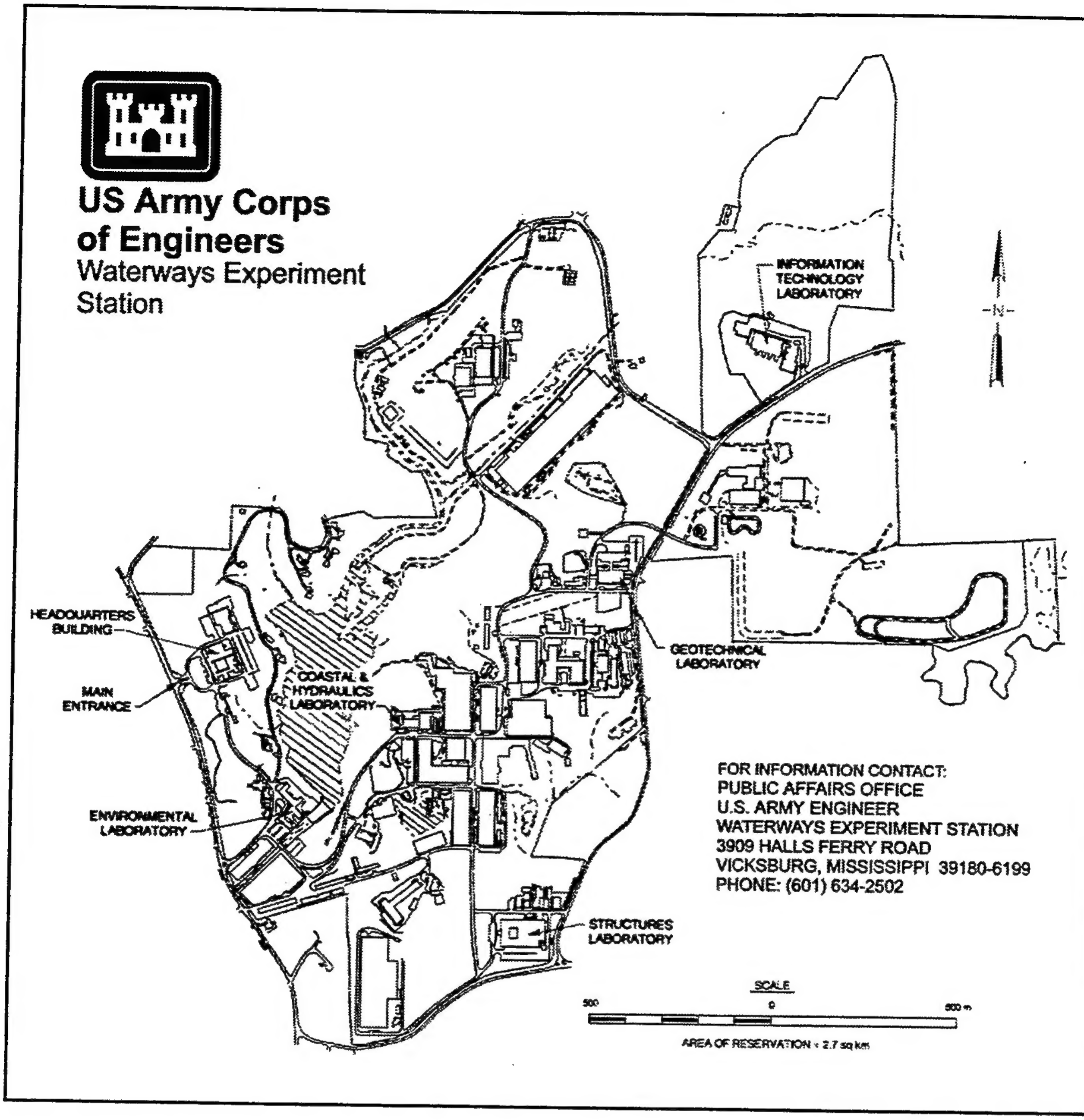

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Preface

The work reported herein was funded under the Operations and Maintenance (O&M) Reliability Models Research Program at the U.S. Army Engineer Waterways Experiment Station (WES). It was performed by Drs. Bilal M. Ayyub and Mark Kaminskiy of BMA Engineering, Inc., under Contract No. DACW-39-94-M-5483 with assistance and guidance from Dr. Mary Ann Leggett and Mr. Robert C. Patev, Computer-Aided Engineering Division (CAED), Information Technology Laboratory (ITL), WES. The work was coordinated with Headquarters, U.S. Army Corps of Engineers (HQUSACE), by Mr. Anil Chowdury of the Operations Division, Directorate of Civil Works, and Messrs. Don Dressler and Jerry Foster of the Engineering Division, Directorate of Civil Works. The authors of the report are Drs. Ayyub and Kaminskiy of BMA Engineering, Inc., and Mr. Patev and Dr. Leggett, WES. The work was performed under the general supervision of Mr. H. Wayne Jones, Acting Chief, CAED, ITL, and Dr. N. Radhakrishnan, Director, ITL.

At the time of publication of this report, Director of WES was Dr. Robert W. Whalin. Commander was COL Bruce K. Howard, EN.

Conversion Factors, Non-SI to SI Units of Measurement

Non-SI units of measurement used in this report can be converted to SI (*System Internationale*) units by applying the following factors:

Multiply	By	To Obtain
feet	0.3048	meters
miles (U.S. statute)	1.6094	kilometers
tons	907.185	kilograms

1 Introduction and Background

This report describes the prediction of loading cycles on miter gates for use in the assessment of fatigue reliability for miter gates. The report explains the correlation of field data for pool and tailwater elevations and barge traffic to form a loading histogram to be utilized to better predict the loading history of a miter gate.

Miter gates at navigation locks experience loading cycles from emptying and filling of a lock's chamber as they are opened to allow traffic through the navigation locks. Reliability analysis of miter gates at navigation locks requires the definition of: (a) nonperformance modes, (b) loads, (c) structural strength, and (d) methods of reliability analysis. Due to the cyclic-loading nature of miter gates, the fatigue of critical details requires examination using reliability methods. The assessment of fatigue reliability of these details as a function of time requires the knowledge of strength, stress ranges, and loading cycles for these details.

The strength of fatigue details can be expressed in the form of *Stress-range versus Number of cycles* (S-N) curves. The determination of stress ranges requires analyzing the reliability of miter gates under different loading conditions. The number of loading cycles needs to be determined also because it constitutes an important component in the reliability analysis, in addition to its use in determining the reliability as a function of time. As a result of the analysis, an evaluation of the remaining life of critical fatigue details in miter gates can be made. The accuracy of the assessed remaining life depends in part on the accuracy in the utilized loading cycles in the reliability analysis.

Objectives

The study that is reported herein had the following objectives:

a. Reviewing previous U.S. Army Corps of Engineers (USACE) studies for determining loading cycles for miter gates at navigation locks.

b. Determining the factors that affect the loading cycles of miter gates at navigation locks.

c. Developing a methodology for computing the number of loading cycles of miter gates at navigation locks.

d. Assessing future traffic using the General Equilibrium Model (GEM)[1], and relating its results to loading-cycles number for miter gates.

e. Demonstrating the use of the GEM for assessing future traffic, and in relating its results to the number of loading cycles.

f. Demonstrating the methodology using a case study.

Literature Review

The fatigue failure mode is commonly considered in detail design, *after* principal structural members have been sized. Several procedures have been used for the assessment of fatigue damage (Wirsching 1984, Wirsching and Chen 1987), such as deterministic methods, Spectral method, Weibull model, and Nolte-Hasford model. For example, the Spectral method was used for marine structures. As was demonstrated by Chen and Mavrakis (1988), the Spectral method is more accurate than the Weibull model for the case of offshore platforms because its results are less sensitive with respect to the variability in the shape of the wave spectra compared to the results of the Weibull model. However, the Spectral method is also the most computationally intensive. Fatigue reliability can be evaluated by using Munse's model (Munse et al. 1982), Wirsching's model (Wirsching 1984), or advanced second moment methods (Madsen, Skjong, and Moghtaderi-Zadeh 1986). A reliability-based design format for fatigue was demonstrated by White and Ayyub (1987).

Fatigue can result from the cyclic loading applied to miter gates of navigation locks as they are operated to perform lockages of vessels going through the locks. Cyclic loading on a gate is generated by the cyclic head and tailwater pressures on the gate. Therefore, variable amplitude stress ranges are applied to critical fatigue details of the gate. These stress ranges cause damage to the details that is cumulative in nature until a crack initiates, then propagates to a possible failure of the affected structural members of the gate. Miner's rule of cumulative fatigue damage under variable amplitude stress range with stress-range versus number of cycles to failure (S-N) information about fatigue details can be used to assess the reliability of the details (American Society of Civil Engineers (ASCE), Committee on Fatigue and Fracture Reliability 1982; White and Ayyub 1987; Ricles and Leger

[1] For convenience, symbols and abbreviations are listed in the notation (Appendix B).

1993; Sommer, Nowak, and Thoft-Christensen 1993; USAEWES 1994). The details of fatigue analysis of miter gates are provided in ETL 1110-2-346 (Headquarters, Department of the Army 1993a). Also, ETL 1110-2-351 (Headquarters, Department of the Army 1993b) covers fatigue analysis of spillway gates.

Fatigue reliability requires the definition of the S-N curves for the fatigue details with their associated uncertainties, and the cyclic variable amplitude stress ranges with their modeling uncertainty in the form of stress range histograms (Ayyub and White 1990; Ayyub, White, and Purcell 1989; Ayyub et al. 1990; USACE 1994; White and Ayyub 1987). Therefore, the data needed for fatigue reliability assessment are (a) types of fatigue details, (b) statistical description of the S-N curves for the fatigue details (Fisher et al. 1970, 1974), (c) materials and their strength and stiffness properties such as the modulus of elasticity and Poisson ratio, (d) structural geometry and dimensions, (e) joint histograms of loading cycles and water heads on both sides of the gate as a function of time, and (f) modeling uncertainties in Miner's rule and computed stresses. The applied loads can also include impact and vibration loads. Their effect on fatigue depends on the occurrence frequency of their stress ranges. Several recent USACE studies on fatigue and concrete deterioration include information on loading cycles of miter gates at navigation locks. These studies were examined for any information and techniques that pertain to this study (Headquarters, Department of the Army 1993a; Headquarters, Department of the Army 1993b; USAEWES 1994).

2 Factors Affecting Loading Cycles

The number of loading cycles for miter gates is a random variable with inherent uncertainty resulting from sources that include the following:

a. Navigation traffic volume.

b. Traffic composition primarily in terms of tow length.

c. Length and capacity of navigation locks.

d. Traffic direction and pattern.

e. Weather-related conditions, e.g., ice buildup and debris.

f. Impact loads.

The loading cycles need to be expressed in a form that is suitable for computing variable-amplitude stress ranges with associated loading cycles. Therefore, the loading cycles should be related to pool and tailwater elevations.

The navigation traffic volume is an important factor in determining the number of cycles. The number of cycles is increased by increasing the traffic volume. However, the relationship is complicated by the traffic composition in terms of tow-length distribution. Tows are typically longer than most navigational locks, and are passed through a lock in several sections or cuts and reassembled afterwards. The number and length of the cuts in a tow is dependent upon the lock's dimensions.

Traffic in navigation locks can be in either an upstream or downstream direction or both. In cases where the traffic includes the simultaneous upstream and downstream movements, the gates can be operated more efficiently by alternating between the two types of traffic, hence utilizing each loading cycle of the gates in moving the traffic.

Winter weather conditions affect the loading cycles, especially ice buildup in the upper approach regions of locks. Some locks are completely closed to river traffic during the winter because of ice buildup on the river; other locks are operated year-round. Sometimes, miter gates are operated for the purpose of passing ice flows to reduce ice buildup in the upper approach, and to relieve any pressure on

the gates. The loading cycles for managing the ice flow are usually not recorded in operational logs (Patev 1995).

Sometimes barges or boats apply a load to miter gates due to unintentional impact resulting from poor judgment of tow operators, poor hydraulic conditions, or inclement weather. Even though these impact loads can cause damage to the gates, they are not considered in this report for assessing fatigue reliability.

3 Information Sources for Assessing Loading Cycles

Lock Performance Monitoring System (LPMS)

The USACE Lock Performance Monitoring System (LPMS) includes information such as lock number, lockage date, start of lockage, direction of lockage, number of cuts, entry type, exit type, end of lockage, and tonnage. LPMS entries can be used to compute loading cycles needed for fatigue-reliability evaluation. However, the computation of these cycles from the LPMS can require a significant level of effort due to the structure of LPMS.

Lockmaster Records

Lockmasters maintain records that might contain information on loading cycles of miter gates. For this study several navigation locks were selected for a field trip after consultation with USACE. A field trip to the sites of these locks was undertaken. The records of the locks were examined. Information that can be used in developing the methodology for this study was gathered. The field trip included Locks and Dams 22, 24, and 25 on the Mississippi River.

Hydraulic Records

Hydraulic-operation records include pool and tailwater elevations that can be obtained on daily basis. These records are needed for assessing loading cycles with associated water heads. The USACE records were found to be suitable for water-head load estimation. The pool elevation (or height) of water (H_p) and the tail elevation (or height) of water (H_t) are needed. These quantities need to be computed on a daily basis starting from the beginning of the LPMS (i.e., January 1980) to the present. The heights (H_p,H_t) can be used to compute stresses and stress ranges at critical fatigue locations, whereas the number of repetitions of the pairs (H_p,H_t) produces the needed frequency of the corresponding stress ranges. Therefore, stress-range frequency histograms necessary for fatigue analysis can be produced. The number of repetitions of the pairs (H_p,H_t) can be computed from data in the LPMS.

Uncertainty in Loading Cycles

The number of loading cycles for miter gates is considered in this study to be a random variable. The sources of uncertainty in assessing loading cycles are due to the factors discussed previously. The uncertainty in the number of loading cycles can be expressed using a probability distribution for this number. Also, the water elevations with the associated loading cycles need to be expressed in probabilistic terms. Prediction models that can be developed based on statistical analyses of data include statistical variability that needs to be assessed. Modeling uncertainty that is associated with computing stresses at critical fatigue locations of miter gates needs also to be considered in performing fatigue reliability assessment.

4 Methodology for Determining Loading Cycles

Stages for Computing Loading Cycles

The methods needed for determining loading cycles for miter gates is dependent upon the nature of available information. The type of available information depends on the years (i.e., time period) of interest. Loading cycle estimates should cover the entire life of a gate since these estimates are needed for fatigue analysis. The life of the gate can be viewed to consist of its present age plus the planned remaining life. Estimates of loading cycles up to the present can be determined using methods that depend on the type of available information. Estimates of future loading cycles need to be based on forecasting models of future traffic in navigation channels.

In this chapter, the terms lockage, lockage cut, hydrostatic loading cycles, and hardware cycles are used. In general, a lockage is defined as a series of events required to transfer a tow or vessel with all its barges through a lock in a single direction. For the purposes of this report, a lockage cut is defined as a process of passing one cut of a tow or several vessels together through a lock. This process requires the operation of the gates of the lock (the emptying and filling of a lock's chamber) once, if the gates are favorably positioned to an inbound cut of a vessel. If a vessel can be accommodated in the lock in its entirety, then one emptying and one filling of the lock's chamber are required. Also, if several vessels can be simultaneously accommodated in the lock, then one emptying and one filling of the lock's chamber are required. However, if a vessel is too large to be accommodated in the lock, it is separated in two or more cuts. Several lockage cuts in this case are required in order to pass through all the cuts by emptying and filling the lock's chamber several times. The number of lockage cuts in this case is equal to the number of cuts passed in the lock. If a lock's state is not in a favorable position to receive an inbound vessel, an additional cycle of emptying and filling of the lock's chamber is required. A hydrostatic loading cycle consists of a complete emptying *and* filling of a lock's chamber that produces a hydrostatic water-head differential on the gates. A hardware cycle is a complete emptying *or* filling of a lock's chamber that produces a hydrostatic water-head differential on the gates. Therefore, a hydrostatic loading cycle consists of two hardware cycles.

A key source of information for estimating loading cycles on miter gates is the USACE LPMS. The LPMS generally covers the period from 1980 to present. The time period before 1980 can be broken down into several stages depending on the available information. For example, it can be broken down into two stages, start of life (completion of construction, e.g., around late 1930's and early 1940's for most locks on the Mississippi River) to 1948, and 1948 to 1980. It seems that formal traffic record keeping for these locks was not established until the late 1940's.

In consideration of the above description of the nature of available information on the utilization of locks, the following stages can be identified for developing methods for estimating loading cycles:

Stage 1: Start of life (e.g., 1940) to 1948.

Stage 2: 1948 to start of the LPMS (i.e., 1980).

Stage 3: Start of LPMS (1980) to present.

Stage 4: Present to planned design (or rehabilitation) life.

In this chapter, methods for assessing loading cycles for these stages were developed. Stage 3 (i.e., the LPMS stage) contains information of the highest levels of data quality and certainty. Therefore, this stage can be used as a basis for estimating some of the parameters in other stages as described below.

Loading cycles for Stage 3 (start of LPMS to present)

This stage contains the best and needed information to evaluate loading cycles on miter gates. The primary source of information is the LPMS; therefore, this stage is called hereafter the LPMS stage.

In the LPMS stage, the following quantities are of interest: (a) pool elevation (or height) of water (H_p), (b) tail elevation (or height) of water (H_t), and (c) the corresponding number of repetitions of the pair (H_p,H_t). Due to the observed daily variability in the water elevations, these quantities need to be computed on a daily basis starting from January 1980 to present. The heights (H_p,H_t) can be used to compute stresses and stress ranges at critical fatigue locations, whereas number of repetitions of the pairs (H_p,H_t) produces the needed frequency of the corresponding stress range. Therefore, stress-range frequency histograms that are necessary for fatigue analysis are produced. The daily upper and lower water pool

heights (H_p,H_t) can be obtained from the hydraulic records of a lock as discussed in Chapter 3.

The number of repetitions of the pairs (H_p,H_t) can be computed from data in the LPMS. The fields of the LPMS that are shown in Table 1 can be utilized for this purpose. These fields are defined in the LPMS user's manual (USACE 1990). The number of hardware cycles in a day (LR-SHFT-DY) for a selected month (LR-SHFT-MO), a selected year (LR-SHFT-YR), and a selected lock (LR-LOCK) can be computed from Table 1 by considering for the start of lockage, end of lockage, entry type, exit type, vessel type, and direction of traffic in its computation. Several algorithms were developed to compute hardware cycles from the fields in Table 1. Some of these algorithms produced erroneous results due to some ambiguity in the meaning of some fields of the LPMS. Considering these trials, some fields of the LPMS can be improved to facilitate the computations of hardware cycles. For example, the following observations are made:

a. The current entry and exit types do not necessarily reflect the turnback type, if it was delayed, i.e., not immediate to an entry or exit, respectively. Depending on the use of these fields in their current forms, either new fields should be developed that correct for the delayed turnback occurrence, or the current fields should be revised.

b. Sometimes several vessel records were entered in the LPMS as separate lockages, but these vessels were serviced in the same operation of opening and closing of miter gates. The LPMS does not keep track of these cases, thereby complicating the computation of hardware cycles. The start of a lockage and end of a lockage were used to account and correct for this factor.

c. Ice and debris lockages are not included in the LPMS. The results of time-lapsed videotapes of Locks 22 and 25 were used to assess these cycles (Patev 1995).

d. The operations of the gates for service, inspection, or performance evaluations are not recorded in the LPMS.

Considering the above, the daily numbers of hardware cycles were computed using the following logic:

a. The number of cuts NC (i.e., LR-NO-CUTS field) was corrected to account for cases that involve several vessels serviced by the same lockage. Therefore, a new field was added to Table 1 called the corrected number of cuts (CNC). The entry of this field for the ith record in a

month was computed using the following logic statement in spreadsheet form:

$$CNC(i) = IF(AND(DY(i) = DY(i+1) , OR(ABS(SOL1(i+1) - SOL1(i)) <= 13, ABS(EOL1(i+1) - EOL1(i)) <= 10) , NC(i+1) = NC(i) , VT(i) <> \text{“R”}) , NC(i) - 1 , NC(i)) \quad (1)$$

The variables in Equation 1 are defined in Table 1, where, for example, $DY(i)$ = day of shift for the $i\underline{th}$ record in a month, and $VT(i)$ <> "R" means the vessel type of this record does not equal "R" which corresponds to a recreational vessel. Equation 1 is based on an EXCEL (Microsoft©) logical statement of the following type:

IF(*logical expression* , *expression if* TRUE , *expression if* FALSE) (2)

b. Another new field was introduced called hardware cycles (HC) for the $i\underline{th}$ record in a month. This field was computed using the following logic statement:

$$HC(i) = 2*CNC(i) - 1 + IF(DR(i) = DR(i+1) , 1 , 0) \quad (3)$$

c. The daily number of hardware cycles was then computed by totaling the values of $HC(i)$ over all i values (i.e., records) that are in the same day.

d. The daily number of lockages (LG) was then computed by totaling the values of $CNC(i)$ over all i values (i.e., records) that are in the same day.

e. The daily hardware-cycle and lockage numbers were then corrected by adding cycles needed to pass through ice and debris. These additional cycles can be estimated based on time-lapsed videotapes, if available.

f. The monthly number of hardware cycles was then computed by totaling the values of items *c* and *e* over each month.

g. The monthly number of lockages was then computed by totaling the values of items *d* and *e* over each month.

Table 1
Selected Fields from the LPMS

Field Number	Field Name	Description
1	LR-LOCK	Lock Number (LN)
7	LR-SHFT-MO	Month of Shift (MO)
8	LR-SHFT-DA	Day of Shift (DY)
9	LR-SHFT-YR	Year of Shift (YR)
10	LR-SOL-1	Start of Lockage Time (24 hr) 1st Cut (SOL1)
12	LR-DIR	Direction of Lockage (up or down) (DR)
13	LR-NO-CUTS	Number of Lockage Cuts (NC)
14	LR-LCKG-TYPE	Lockage Type (LT)
15	LR-VSL-TYPE	Vessel Type (VT)
18	LR-ENTRY-TYPE	Entry Type (ET)
19	LR-EXIT-TYPE	Exit Type (XT)
26	LR-EOL-1	End of Lockage Time (24 hr) First Cut (EOL1)
31	LR-EOL-2	End of Lockage Time (24 hr) Last Cut (EOL2)
78	LR-TONS	Tonnage (TN)

The logic above is based on the assumption that the idle gate position of a lock is its position at the end of the previous lockage. The logic above accounts for the additional hydrostatic loading cycles needed to position the gates in a favorable position for receiving incoming vessels to the lock. This effect was accounted for by considering the sequences for the direction of traffic. The entry and exit types recorded in the LPMS were found to be unsuitable for this purpose because these entries show only the immediate entry or exit types, respectively.

The data reduction and analysis of the hydraulic records and the LPMS's fields produce daily quantities for pool water elevation (H_p), tailwater elevation (H_t), number of hardware cycles (HC), and number of lockage cuts (LGC). These results can be used to compute the loading cycles of interest by following the steps below:

Step 1. Use curve-fitting to develop a relationship between pool water elevation and tailwater elevation. The result can be expressed as pool water elevation as a function of tailwater elevation.

Step 2. Sum the numbers of hardware cycles for intervals of tailwater elevations. Normalizing the number of hardware cycles by the total number of hardware cycles produces tailwater elevations with associated fractions of hardware cycles, i.e., a histogram of tailwater elevation in which tailwater elevation is treated as a loading.

Step 3. Fit a probability density function to the histogram from Step 2.

Step 4. Determine the total number of hardware cycles and lockage cuts on monthly and yearly bases from the daily records.

Step 5. Use curve-fitting to establish relationships among the following variables: hardware cycles, lockage cuts, tonnage, and time. The tonnage for a lock over some time period can be computed from the fields of LPMS as the total weight of commodities that pass through the lock within this time period. These relationships are needed in other stages as discussed below. The relationships can be developed using monthly or annual records.

The models that result from Steps 3 and 5 constitute the basis for assessing the loading cycles. These models can be expressed in dimensionless format by normalizing them with respect to corresponding design values. For example, the tailwater loading probability density function (Step 4) can be normalized with respect to the tailwater elevation design value for an investigated lock. The benefit of expressing the results in a normalized format is in potentially increasing the range of applicability of the results to other locks. In general, locks and dams along a river can be classified into groups (or reaches). A typical lock can be analyzed from each reach and several locks in a selected reach can be analyzed to produce a complete understanding of loading cycles on miter gates. Future work in this area can examine the relationships and variability among the reaches and within reaches.

Loading cycles for Stage 1 (start of life to 1948)

Stage 1 is defined as the stage from the start of life of a lock to about 1948. The end of this stage (i.e., 1948) was established based on the record-keeping practices of the USACE for locks on the Mississippi River. This stage can be characterized as a stage with inadequate records that are needed to compute loading cycles. Generally, the information available from records in this stage is limited to annual tonnage. Therefore, the relationships of hardware cycles and lockage cuts as functions of tonnage that were developed in the LPMS (third) stage can be used to estimate hardware cycles and lockage cuts, respectively, for this stage. Alternatively, the number of hardware cycles as a function of time and the number of lockage cuts as a function of time that were developed in the LPMS stage can be used to estimate these quantities by extrapolation. The former approach is recommended in this report because its results are partly based on data in the first stage.

Loading cycles for Stage 2 (1948 to start of LPMS)

Stage 2 is defined as the stage from about 1948 to the start of the LPMS stage. The start of this stage (i.e., 1948) was established based on the record-keeping practices of the USACE for locks on the Mississippi River. This stage can be characterized as a stage with better records than the first stage that are needed to compute loading cycles. Generally, the available information in this stage is limited to annual lockages and annual tonnage. Therefore, the relationships of hardware cycles and lockage cuts as functions of tonnage that were developed in the LPMS (third) stage can be used to estimate hardware cycles and lockages, respectively. Alternatively, the number of hardware cycles as a function of time and the number of lockages as a function of time that were developed in the LPMS stage can be used to estimate these quantities using extrapolation.

Loading cycles for Stage 4 (present to planned end of design life or rehabilitation)

Stage 4 starts from the present and ends with the planned end of design (or rehabilitation) life of a lock. The models in this stage can be based on forecasting techniques. The scope of this report does not include the development of forecasting models. However, the USACE General Equilibrium Model (GEM) (USACE 1994) can provide forecasts of annual tonnage as a function of time based on a set of input variables. The predictions of traffic volumes are expressed in the forms of low, medium, and high tonnage predictions as functions of time. Therefore, the relationships of hardware cycles and lockages as functions of tonnage that were developed in the LPMS (third) stage can be used to estimate hardware cycles and lockage cuts, respectively, for this stage.

Probabilistic Model

The objective of the model proposed below is to predict the number of hardware cycles on miter gates as a function of either the number of vessels passing through a lock or the number of lockage cuts that occur at a lock. The model accounts for the following factors: (a) navigation traffic volume, (b) traffic composition in terms of vessel lengths, (c) length and capacity of navigation locks, (d) traffic pattern (in terms of upstream/downstream ratio), and (e) non-vessel lockages (loading cycles connected with passing ice and debris).

Relationship between number of hardware cycles and number of vessels (i.e., traffic volume)

The development of the relationship between the number of hardware cycles and the number of vessels (or traffic volume) is divided into the following four cases:

a. The increase in the number of hardware cycles due to cutting of long vessels, assuming the traffic is in one direction.

b. The effect of simultaneous lockages of light boats or recreational vessels.

c. The decrease in the number of hardware cycles due to travel in opposite (upstream and downstream) directions.

d. The effect of environmental conditions (debris and ice lockages).

These four cases are discussed below.

Increase in number of hardware cycles due to cutting of long vessels. The maximum length (l_{max}) of a vessel that can be locked in one operation of a lock and the cumulative distribution function of length of the vessel population ($F_L(l)$) determine the number of needed cuts. The length of the vessel population is a discrete random variable with the following cumulative distribution function:

$$F_L(l) = \sum_{for\ l_i \leq l} p_L(l_i) \qquad \text{for } i = 1,2,\ldots, NL \tag{4}$$

where $p_L(l_i)$ = probability mass value for a vessel of a length l_i for NL possible discrete vessel lengths. The continuous approximation of this distribution function is an integral of the corresponding probability density function $f_L(l)$:

$$F_L(l) = \int_0^l f_L(x)dx \tag{5}$$

The arrival of vessels in one direction at a lock can be assumed to follow a Poisson distribution with a rate λ . For a time period of interest (T), which is nonrandom, the mean number of vessels that arrives at the lock during the time T is

$$\overline{N}_v = \lambda T \tag{6}$$

where $\overline{N}_v$ = mean number of vessels arriving in time T. The probability (P_1) that a vessel is not cut in two or more parts is given by

$$P_1 = F_L(l_{\max}) \tag{7}$$

The probability (P_2) that a vessel is cut in two parts is given by

$$P_2 = F_L(2\,l_{\max}) - F_L(l_{\max}) \tag{8}$$

Analogously, the probability (P_k) that the vessel is cut in k parts is given by

$$P_k = F_L(k\,l_{\max}) - F_L[(k-1)\,l_{\max}] \tag{9}$$

where k = number of parts into which vessels can be cut. In general, the probability that for a given number of vessels N_v exactly N_1 vessels will not be cut, N_2 will be cut in two parts, and so on, is given by the multinomial distribution with parameters N_v, P_1, P_2,..., P_k.

The probabilities P_1, P_2,..., P_k should satisfy the following condition:

$$\sum_{i=1}^{k} P_i = 1 \tag{10}$$

If N_v (the number of vessels that arrive at a lock in one direction during reference time period T) is a nonrandom variable, the number of vessels with one or more parts (i = 1,2,...,k parts) due to cutting has the following mean ($\overline{N}_1$), and variance ($Var(N_1)$), respectively:

$$\overline{N}_1 = N_v P_1 \tag{11}$$

and

$$Var(N_1) = N_v P_1 (1 - P_1) \tag{12}$$

The number of vessels which are cut in two parts has the following mean ($\overline{N}_2$) and variance ($Var(N_2)$), respectively:

$$\overline{N}_2 = N_v P_2 \tag{13}$$

and

$$Var(N_2) = N_v P_2 (1 - P_2) \tag{14}$$

The number of vessels which are cut in k parts has the following mean ($\overline{N}_k$) and variance ($Var(N_k)$), respectively:

$$\overline{N}_k = N_v P_k \tag{15}$$

and

$$Var(N_k) = N_v P_k (1 - P_k) \tag{16}$$

For an inbound vessel to a lock with its gates in a favorable position (i.e., a fly entry with lock chamber pool at incoming elevation) that needs to be cut into i parts, the number of hardware cycles ($\overline{N}_{HCi}$) is related to N_v and P_i according to Equation 3 as

$$\overline{N}_{HCi} = (2i-1) N_v P_i \qquad \text{for } i = 1, 2, ..., k \tag{17}$$

Therefore, the mean of the total number of hardware cycles ($\overline{N}_{HC}$) can be related to the number of vessels as

$$\overline{N}_{HC} = N_v (P_1 + 3P_2 + 5P_3 + ... + (2k-1)P_k) \tag{18}$$

or

$$\overline{N}_{HC} = N_v \left[(\sum_{i=1}^{k} P_i) + 2P_2 + 4P_3 + ... + 2(k-1)P_k \right] \tag{19}$$

Using Equation 10, the mean total hardware cycles can be expressed as

$$\overline{N}_{\Sigma lc} = N_{loc} \left[1 + \sum_{i=2}^{k} (i - 1) P_i \right] \tag{20}$$

The variance of the total number of hardware cycles can be written as

$$Var(N_{HC}) = N_v^2 \sum_{i=1}^{k} 4(i-1)^2 P_i(1-P_i) \tag{21}$$

Decrease in number of hardware cycles due to simultaneous lockages of small vessels. It is common in operating locks to simultaneously service a number of small vessels, as is the case for light boats and recreational boats. The effect of this practice on hardware cycles is a reduction in its total number. Therefore, the above approach can be generalized to take this decrease into account. Let p_s be the probability that a given boat is being serviced simultaneously with other boats, then the mean total number of hardware cycles should be decreased by the value ΔN_{HC}

$$\Delta N_{HC} = N_v p_s \tag{22}$$

The combination of Equations 19 and 22 produces

$$\overline{N}_{HC} = N_v \left[1 + \sum_{i=2}^{k} 2(i-1) P_i - 2p_s \right] \tag{23}$$

In this case, the following condition needs to hold

$$\sum_{i=1}^{k} P_i + p_s = 1 \tag{24}$$

The mean of the total number of hardware cycles according to Equation 23 is a linear function of the number of vessels for traffic in one direction. For cases where $\overline{N}_{HC} > N_v$, the increase in the number of hardware cycles due to the cutting of long vessels prevails over the decrease in the number of hardware cycles due to simultaneous lockages of small vessels, and vice versa.

In the LPMS database, the number of lockage cuts (N_{loc}) for vessels is defined as

$$N_{loc} = N_{cuts} \tag{25a}$$

where N_{cuts} = number of cuts, then Equation 25a can be rewritten using Equations 11, 13, and 15 as

$$N_{loc} = N_v \sum_{i=1}^{k} iP_i \tag{25b}$$

where N_{cuts} takes the values of 1, 2, 3, ..., k, in which 1 corresponds to a vessel without a cut. In this case, Equations 17, 22, and 23 produce the following:

$$\overline{N}_{HC} = (2N_{loc} - 1) - N_v p_s \tag{26a}$$

Equation 26a can be rewritten using Equation 25b to produce the following relationship between mean total hardware cycles and number of lockages cuts:

$$\overline{N}_{HC} = (2N_{loc} - 1) - p_s \frac{N_{loc}}{\sum_{i=1}^{k} iP_i} \tag{26b}$$

Decrease in number of hardware cycles due to travel in opposite directions. In order to model the effect of two-direction traffic on hardware cycles, let λ_u be the Poisson rate of traffic moving upstream, λ_d be the Poisson arrival rate to a lock for traffic moving in the downstream direction, and N_{vd} and N_{vu} be the overall number of vessels arriving to a lock from downstream and upstream directions during the reference period T, respectively. If δt_d is the service time in the lock for a vessel in the downstream traffic, the mean decrease in the number of hardware cycles (ΔN_{HCd}) for a steady-state traffic is

$$\Delta N_{HCd} = N_{vd} \lambda_{up} \delta t_d \tag{27}$$

Since $N_{vd} + N_{vu} = N_v$, the downstream number of vessels $N_{vd} = N_v(1-\alpha)$, where $0 \leq \alpha \leq 1$, $N_{vu} = \alpha N_v$, and α = fraction of traffic moving upstream. Using the estimate $\lambda_u = N_{vu}/T$, Equation 27 can be expressed as

$$\Delta N_{HCd} = \frac{\alpha(1-\alpha)N_v^2 \delta t_d}{T} \tag{28}$$

Analogously, the mean decrease in the number of hardware cycles due to the traffic in the opposite (upstream) direction is

$$\Delta N_{HCu} = \frac{\alpha(1-\alpha)N_v^2 \delta t_u}{T} \tag{29}$$

where δt_u is the service time in the lock for a vessel in the upstream traffic, and ΔN_{HCu} is the mean decrease in the number of hardware cycles in the upstream traffic. The sum of Equations 28 and 29 is the total decrease in the number of hardware cycles (ΔN_{HCt}), which can be expressed as

$$\Delta N_{HCt} = \frac{\alpha(1-\alpha)N_v^2(\delta t_u + \delta t_d)}{T} \tag{30}$$

Equation 30 makes sound physical sense. For example, the total decrease has a maximum value when the upstream traffic is equal to the downstream traffic, i.e., $\alpha = 0.5$. Equation 30 can be re-written as

$$\Delta N_{HCt} = \frac{\alpha(1-\alpha)N_v^2 2\delta t}{T} \tag{31}$$

where $\delta t = \delta t_{up} + \delta t_{down} / 2$. Table 2 shows estimates of hardware-cycle reduction for selected values of δt and N_v using $\alpha = 0.5$, and T = 8,760 hours (i.e., one year).

Table 2
Estimates of Hardware-Cycle Reduction for Selected Values of δt and N_v Using $\alpha = 0.5$

dt (hours)	For N_v = 1,000 vessels per year	For N_v = 2,000 vessels per year
0.25	14	57
0.5	29	114
1	57	228
2	114	457
3	171	685
4	228	913

A strong seasonal variation in the number of vessels can result in considerable variation of α. Thus, in this case, the number of vessels passing through the lock cannot be considered to be a Poisson process. Under this restriction, Equation 6 needs to be used as follows:

a. The reference time period in this case can be taken as a month, i.e., T_i where i = 1, 2,..., 12.

b. The fraction of upstream traffic is α_i, which is related to the *ith* month.

c. The number of vessels in the ith month is N_{vi}, so that if N_v is the annual number of vessels, then

$$N_{vi} = \beta_i N_v \tag{32}$$

where β_i is the fraction of vessels in the ith month from the traffic of a year. Therefore, the following condition needs to be satisfied:

$$\sum_{i=1}^{12} \beta_i = 1. \tag{33}$$

The set of β_i values expresses the monthly distribution of annual traffic in both directions. It should be noted that neither β_i nor α_i depends on the absolute value of the annual number of vessels N_v. Thus, in this case, Equation 31 takes on the following form:

$$\Delta N_{HCt} = \frac{2\delta t N_v^2}{T} \sum_{i=1}^{12} \alpha_i (1 - \alpha_i) \beta_i^2 \tag{34}$$

or

$$\Delta N_{HCt} = \frac{2\delta t N_v^2}{T} K \tag{35}$$

where $K = \sum_{i=1}^{12} \alpha_i (1 - \alpha_i) \beta_i^2$ is a coefficient for expressing seasonal variation in traffic volume and direction.

Hardware cycles due to non-vessel lockages. Some of the hardware cycles for miter gates can be attributed to non-vessel lockages such as the passing of debris and ice especialy during the winter months. If these lockages are recorded in the LPMS as real lockages with the appropriate numbers of hardware cycles, they can be taken into account by the model by adding a term to Equation 23. If these lockages are not recorded in the LPMS, then their hardware cycles can be taken into account by adding a positive constant term in any developed regression models to fit real data for the number of hardware cycles and annual tonnage as described below.

Relationship between hardware cycles and lockages using regression analysis

In this section, an example regression model is developed in order to establish a relationship between hardware cycles and lockage cuts using real data, e.g., based on the LPMS. Equations 23 and 31 can be combined to obtain the following model for monthly data with a constant term (*Constant*) that corresponds to the hardware cycles associated with non-vessel lockages and can be added to the model. This constant would not be needed if these non-vessel lockages were recorded in the LPMS as actual lockages with the appropriate numbers of hardware cycles. The equation for this model is given by

$$\overline{N}_{HC} = N_v\left[1+\sum_{i=2}^{k}(i-1)P_i-2p_s\right]-\frac{\alpha(1-\alpha)N_v^2\,2\delta t}{T}+\text{ Constant} \tag{36a}$$

The mean hardware cycles according to Equation 36a can be expressed in terms of N_{loc} instead of N_v based on Equations 25b and 26b as

$$\overline{N}_{HC} = (2N_{loc}-1)-p_s\frac{N_{loc}}{\sum_{i=1}^{k} iP_i}-\frac{\alpha(1-\alpha)2\delta t}{T}\frac{N_{loc}^2}{\left(\sum_{i=1}^{k} iP_i\right)^2}+\text{ Constant} \tag{36b}$$

or

$$\overline{N}_{HC} = A\,N_{loc}-BN_{loc}^2+C \tag{37}$$

where A, B, C are model coefficients with $B \geq 0$. Figure 1 shows a scatter diagram of lockage cuts and hardware cycles using the annual data that are provided in Chapter 5. The scatter diagram shows a linear relationship between hardware cycles and lockage cuts, i.e., $B = 0$ in Equation 37. A linear regression analysis was then performed. For the case $B = 0$ and $C = 0$, coefficient A has the same meaning as K_c used in the GEM (USACE 1994), i.e., the mean hardware cycles per lockage. An estimate of the correlation coefficient was obtained to be 0.999. The estimates of the coefficients of Equation 37 and their corresponding standard errors are given by

$$\text{A} = 1.67898 \pm 0.0213 \tag{38}$$

$$\text{B} = 0 \text{ (not significant)} \tag{39}$$

$$\text{C} = -55.1587 \pm 134.07 \text{ (not significant)} \tag{40}$$

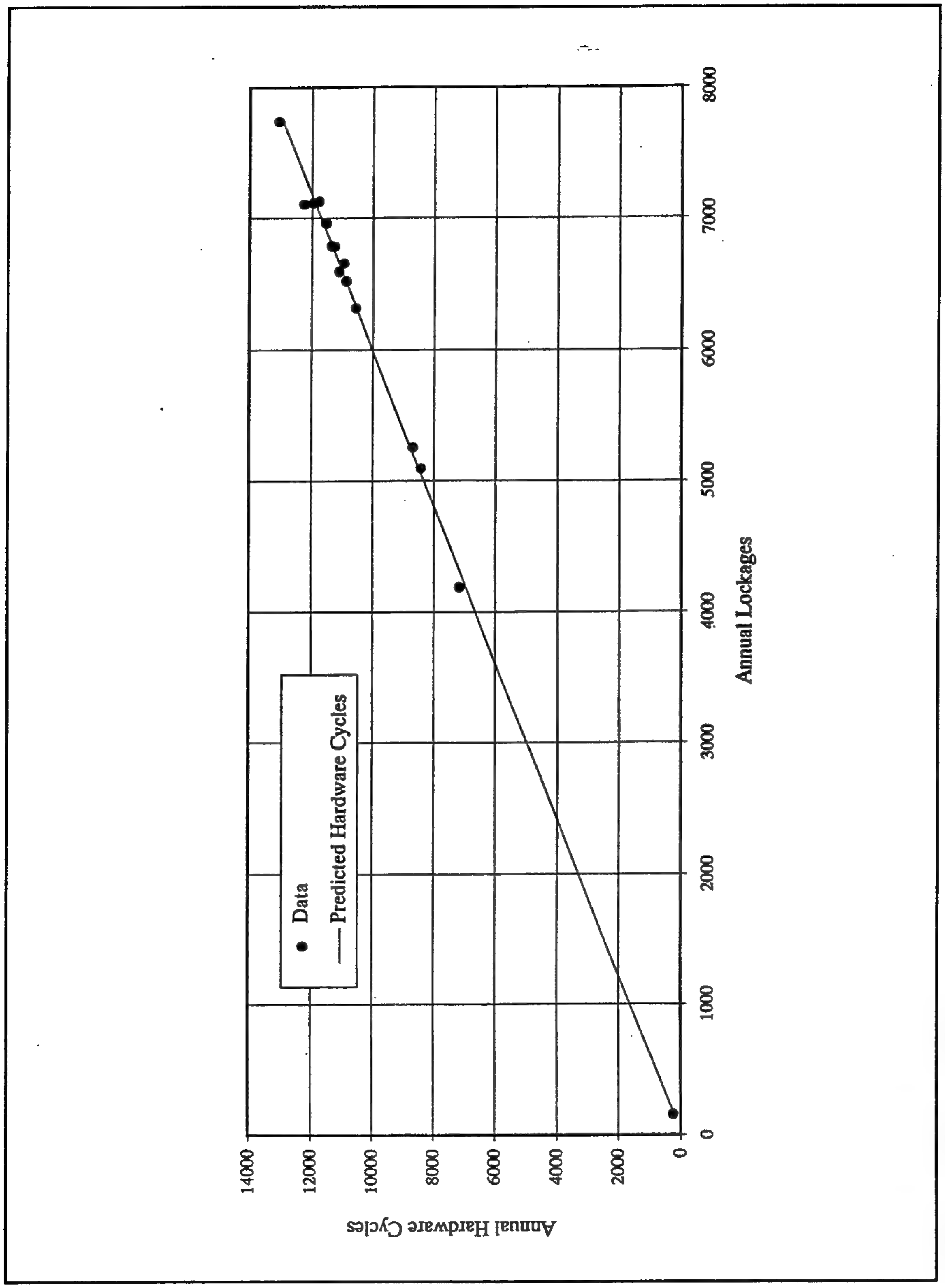


Figure 1. Annual lockages and hardware cycles

Based on the data used in this analysis, only the coefficient A is significant, and should be kept in the model. The developed model is of an adequate precision level for all practical purposes since the standard error of estimates is 148.85 for a sample size of 15 annual values. The results and observations provided herein are lock-specific. For data obtained from other locks, with different patterns of traffic, the significance of the coefficients A, B, and C can be different.

Trend analysis of annual number of lockages

The objective of this analysis is to model the trend of the annual number of lockages for selected locks. The annual number of lockages is considered to follow a Poisson distribution with the following mean

$$N_{loc}(t) = N_0 \exp\left(At + Bt^2 + Ct^3 + \ldots\right) \tag{41}$$

where t is the time in years counted from a specified year (for example 1948 for Locks 11 and 22, and 1940 for Lock and Dam 24). Thus $t = 0$ for 1948 (or 1940), $t = 1$ for 1949 (1941), and so on. The coefficients of the model, i.e., N_0, A, B, and C, are the parameters to be estimated on the basis of curve fitting of the data. In other words, the sequence of annual numbers of lockages is considered to be a realization of a nonhomogeneous Poisson process. To fit the model of Equation 41 to the data, a regression analysis method that was based on counts with logarithmic transformation (Cox and Lewis 1966) was used. The significance of the coefficients was estimated using a stepwise regression procedure. Models for Locks 24, 22, and 11 were fitted. For Lock and Dam 24, the following estimates of the coefficients and their standard errors were obtained using the data in Table 6 for the years 1981 to 1993 and the data provided in the major rehabilitation report for Lock and Dam 24 (USACE 1993c):

$$N_o = 1306.66 \pm 1.06 \tag{42}$$

$$A = 0.050249 \pm 0.003411 \text{ (in years}^{-1}\text{)} \tag{43}$$

$$B = 0 \text{ (not significant)} \tag{44}$$

$$C = -7.4844 \times 10^{-6} \pm 1.2260 \times 10^{-6} \text{ (in years}^{-3}\text{)} \tag{45}$$

The correlation coefficient for the model is 0.955. The variance of the residuals of the annual lockages is 80154.6. The corresponding standard error for the model is 283.1. The accuracy of the model can be also assessed using the sum of fitted values of the number of lockages during the given period. The sum is equal to 225132 which does not differ considerably from the real data value of 227147 (the difference is about 0.9%). The observed and fitted (or predicted using the model) values of annual numbers of lockages are given in Table 3. The results are also shown in Figure 2.

Table 3
Observed and Fitted Annual Number of Lockages for Lock and Dam 24

Year	Observed	Fitted	Year	Observed	Fitted
1940	1718	1307	1971	5250	4964
1941	2212	1374	1972	5584	5104
1942	1409	1445	1973	4914	5242
1943	1050	1519	1974	5157	5375
1944	1119	1597	1975	5058	5503
1945	1213	1678	1976	5386	5625
1946	1817	1763	1977	5235	5741
1947	1705	1853	1978	5668	5849
1948	2178	1946	1979	5778	5949
1949	2551	2043	1980	6601	6040
1950	2258	2144	1981	6788	6121
1951	1990	2249	1982	6319	6193
1952	2027	2357	1983	7108	6253
1953	2335	2470	1984	6595	6302
1954	2435	2587	1985	5099	6338
1955	2981	2707	1986	5262	6363
1956	3146	2831	1987	6523	6373
1957	3288	2959	1988	7131	6370
1958	3386	3090	1989	6787	6354
1959	3698	3224	1990	7743	6324
1960	3408	3362	1991	6963	6280
1961	3365	3502	1992	7228	6222
1962	3801	3644	1993	4189	6150
1963	3827	3789	1994	NA	6064
1964	4084	3935	1995	NA	5965
1965	3585	4083	1996	NA	5854
1966	4078	4231	1997	NA	5729
1967	4211	4379	1998	NA	5594
1968	4688	4527	1999	NA	5447
1969	4344	4675	2000	NA	5290
1970	4938	4820	NA = not applicable or not available		

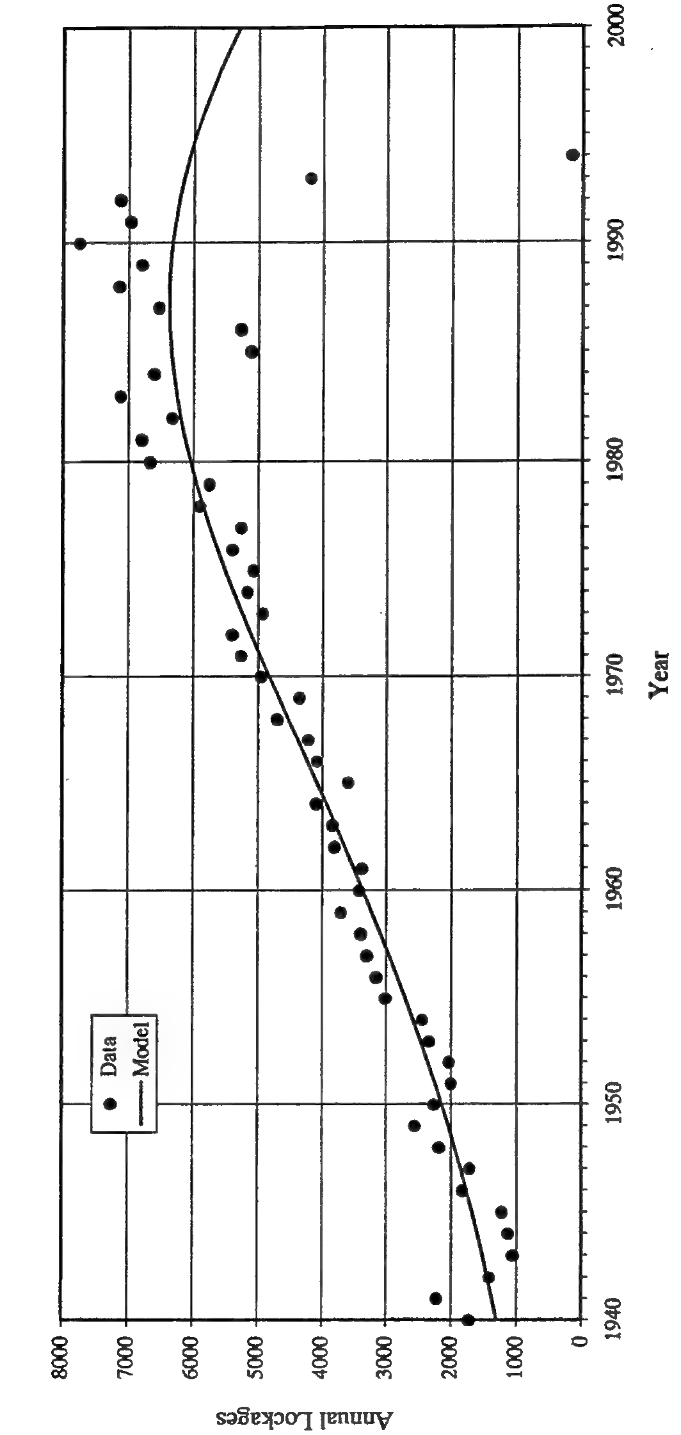


Figure 2. Observed and fitted annual number of lockages for Lock and Dam 24

For Lock 22 the following estimates of the model coefficients and their standard errors were obtained using data provided by the USACE:

$$N_o = 624.53 \pm 1.02 \tag{46}$$

$$A = 0.08392 \pm 0.00256 \text{ (in years}^{-1}) \tag{47}$$

$$B = 0 \text{ (not significant)} \tag{48}$$

$$C = -0.00002 \pm 2.5 \times 10^{-6} \text{ (in years}^{-3}) \tag{49}$$

The correlation coefficient for this model is 0.996. The observed annual number of lockages and the fitted ones using the above models are given in Table 4. The results are also shown in Figure 3.

For Lock 11 the following estimates of the model coefficients and their standard errors were obtained using data provided by the USACE:

$$N_0 = 388.00 \pm 1.04 \tag{50}$$

$$A = 0.10932 \pm 0.00571 \text{ (in years}^{-1}) \tag{51}$$

$$B = -0.00147 \pm 0.00017 \text{ (in years}^{-2}) \tag{52}$$

$$C = 0 \text{ (not significant)} \tag{53}$$

In this case, the correlation coefficient for the model is 0.992. The observed annual number of lockages and the fitted ones using the above models are given in Table 4. The results are also shown in Figure 3.

Number of lockages as a function of tonnage

For cases where data on the annual number of lockages are absent but the annual tonnage data are available, the relationship between annual number of lockages and tonnage can be useful to estimate the number of lockages. This relationship can be obtained on the basis of data analysis for the periods where both lockages and tonnage information is available.

The model development requires the knowledge of the number of lockages and the corresponding tonnage for a number of years. For each record value of annual number of lockages, the corresponding annual tonnage value is needed. This model does not explicitly account for recreational boats which do not have tonnage values. Therefore, the 4annual number of lockages N_{loc} can be related to annual tonnage T_n (in kilotons) as

$$N_{loc} = AT_n + C \tag{54}$$

where the coefficient C can be associated with recreational-boat lockages, or with passing ice or debris. The estimation of the coefficients for this model using Lock and Dam 24 annual data for the period 1940 to 1993 produced the following estimates for the coefficients: C = 1682.60 ± 92.13, and A = 0.1432648 ± 0.00424. The standard error of estimates for the model is 395.96 based on 54 annual values. The correlation coefficient between annual tonnage and number of lockages is 0.978.

Table 4
Observed and Fitted Annual Number of Lockages for Locks 22 and 11

Year	Lock 22		Lock 11	
	Observed	Fitted	Observed	Fitted
1948	630	625	394	388
1949	695	680	447	432
1950	830	738	525	480
1951	782	803	526	531
1952	755	872	474	587
1953	928	948	585	646
1954	1015	1029	699	709
1955	1159	1116	863	776
1956	1197	1210	870	847
1957	1298	1309	894	921
1958	1466	1417	1092	999
1959	1580	1531	1130	1081
1960	1646	1651	1223	1166
1961	1660	1779	1221	1254
1962	1849	1914	1321	1344
1963	2136	2056	1544	1437
1964	2229	2204	1514	1531
1965	2252	2358	1448	1627
1966	2636	2517	1800	1724
1967	2692	2681	1839	1822
1968	2731	2851	1698	1919
1969	3023	3023	1961	2015
1970	3540	3198	2381	2110
1971	3450	3374	2282	2203
1972	3919	3550	2596	2294
1973	3624	3724	2248	2381
1974	3917	3895	2510	2464
1975	3821	4061	2331	2543
1976	3985	4221	2403	2616
1977	4024	4371	2563	2683
1978	4590	4512	2842	2745
1979	4530	4641	2720	2800
1980	5182	4756	3172	2846

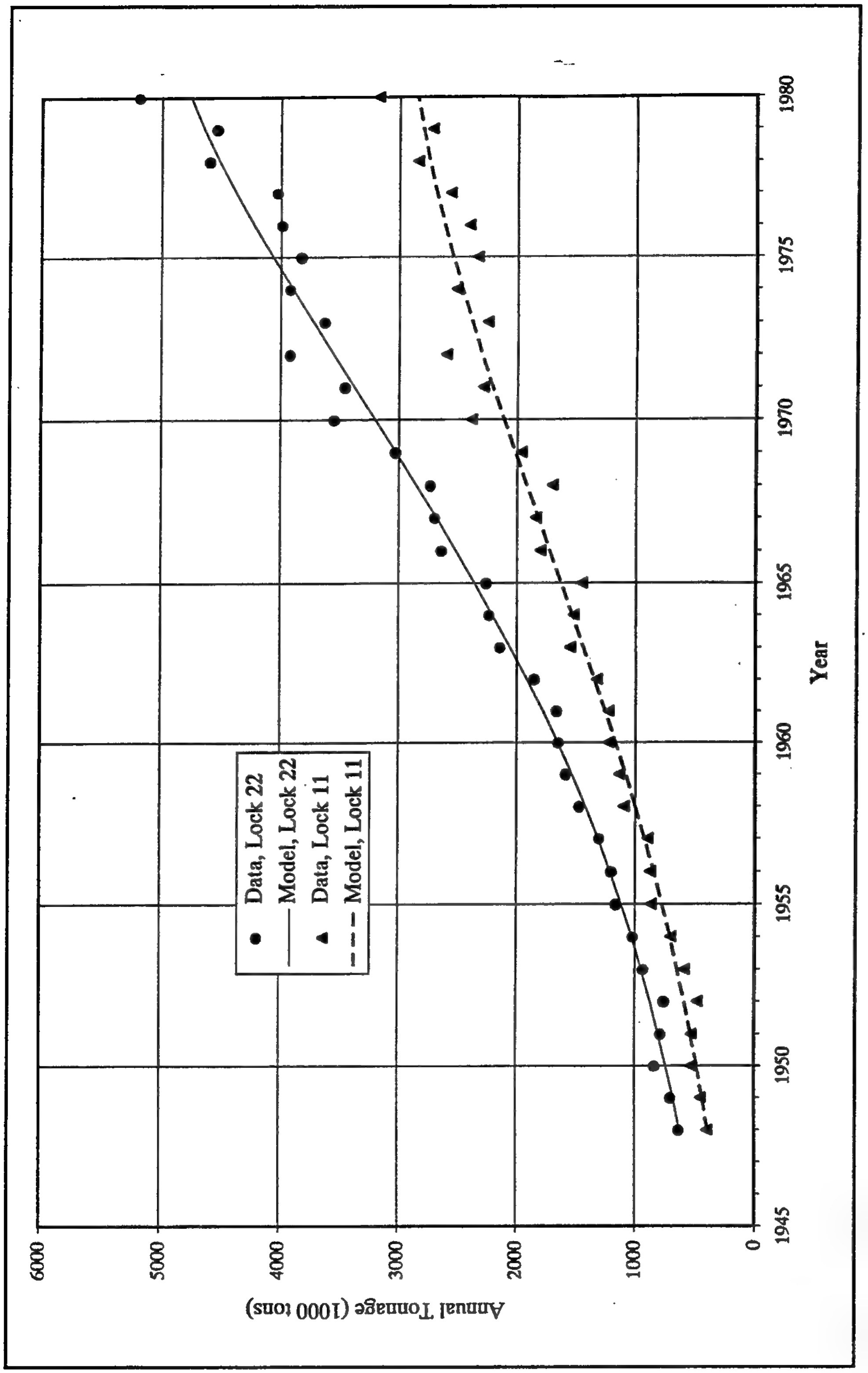


Figure 3. Observed and fitted annual number of lockages for Lock and Dam 22 and Lock and Dam 11

Estimating the cumulative number of hardware cycles

In this section, the cumulative number of hardware cycles is estimated for Lock and Dam 24 over the period 1940 to 2000 for demonstration purposes. The estimation of the accumulated number of hardware cycles can be based on (a) Equation 37 which was obtained from the LPMS data for the period 1980 to 1992 for Lock 24, and (b) the estimated annual data on number of lockages for Lock 24 for the time period from the start of life of 1940 to 1981 based on Equation 54.

Using Equation 41 for the annual number of lockages as a function of time and Equation 34, the accumulated number of hardware cycles were predicted to the year 2000. The results are summarized in Table 5. Table 5 includes also error estimates based on the actual and estimated lockages and hardware cycles. These error values range from +0.4% to -2.9%.

Table 5
Total of Lockages and Hardware Cycles for Lock and Dam 24

Time Period	Actual Lockages (Estimated Lockages ; % Error)	Actual Hardware Cycles (Estimated Hardware Cycles :% Error)
1940 to 1979	136,919 (137,445 ; +0.4%)	NA (228,561, NA)
1980 to 1993	90,279 (87,686 ; -2.9%)	150,805 (146,450 ; -2.9%)
1994 to 2000	NA (39,943 ; NA)	NA (66,677 ; NA)
1940 to 2000	NA (227,360 ; NA)	NA (441,688 ; NA)

NA = not available

It should be noted that the annual number of lockages can also be predicted based on economic forecasts in terms of annual tonnage values using for example the GEM model (USACE 1994), and a relationship between the number of lockages and tonnage similar to Equation 54. This prediction can be more accurate than using Equation 41. A combination of the two approaches can also be used.

5 Lock and Dam 24 - Case Study

Introduction

The objective of this chapter is to demonstrate the use of the methodology as described in Chapter 4 for assessing the number of hardware cycles for example miter gates at a navigation lock. The miter gates of Lock and Dam 24 were selected for this purpose and are the sames gates used in Chapter 4 to demonstrate some aspects of the methodology.

Pool and Tailwater Elevations

The hydraulic records for Lock and Dam 24 were obtained for the period 1975 to 1994. The daily hydraulic information on pool and tailwater elevations were obtained from the USACE. Figures 4a and 4b show these variations on a daily basis for pool and tailwater elevations, respectively. These figures demonstrate clearly the daily variability in water elevations, hence the need for modeling the problem on a daily basis, not monthly nor annually. Figures 5a and 5b show these variations on a daily basis for the years 1975 to 1994 for pool and tailwater elevations, respectively.

In operating a lock and dam, a lockmaster tries to maintain a pool water level by adjusting the dam's gates. However, several factors contribute to the variability in the pool water elevation; e.g., increased flow levels in the river and actions by the lockmasters of upstream and downstream locks to control pool water levels. Adjustments to a dam's gates result in changes in the tailwater elevation as well as the pool water elevation. Therefore, pool and tailwater elevations are expected to be highly correlated. The pool water elevation for Lock and Dam 24 was plotted as a function of the tailwater elevation in Figure 6. From this figure, the following three regions were identified and are described in subsequent sections:

a. Low tailwater elevation, $H_t < 439$ ft.

b. Medium tailwater elevation, $439 \text{ ft} \leq H_t < 445.062$ ft.

c. High tailwater elevation, $H_t \geq 445.062$ ft.

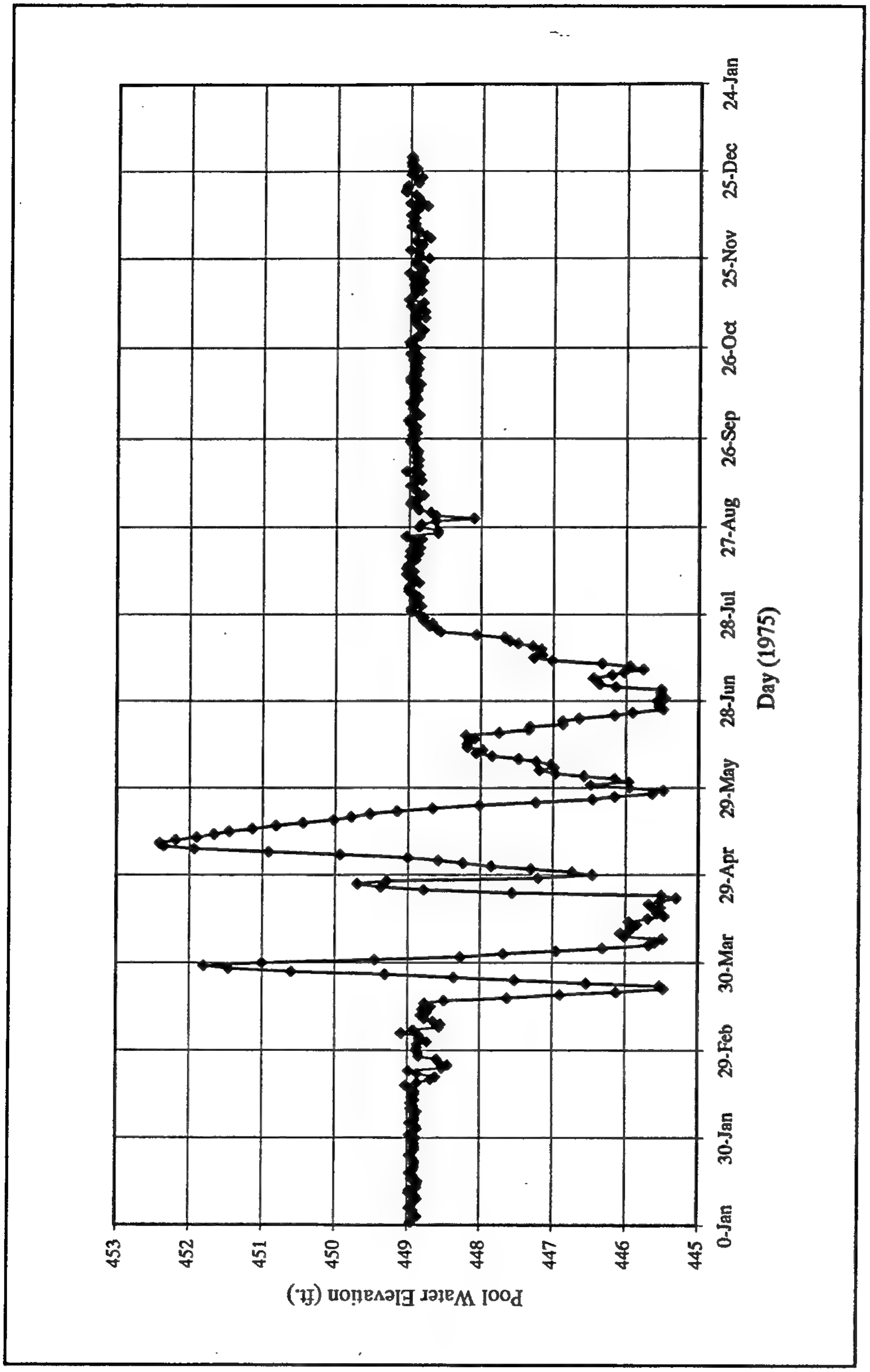


Figure 4a. Pool water elevations in 1975 for Lock and Dam 24

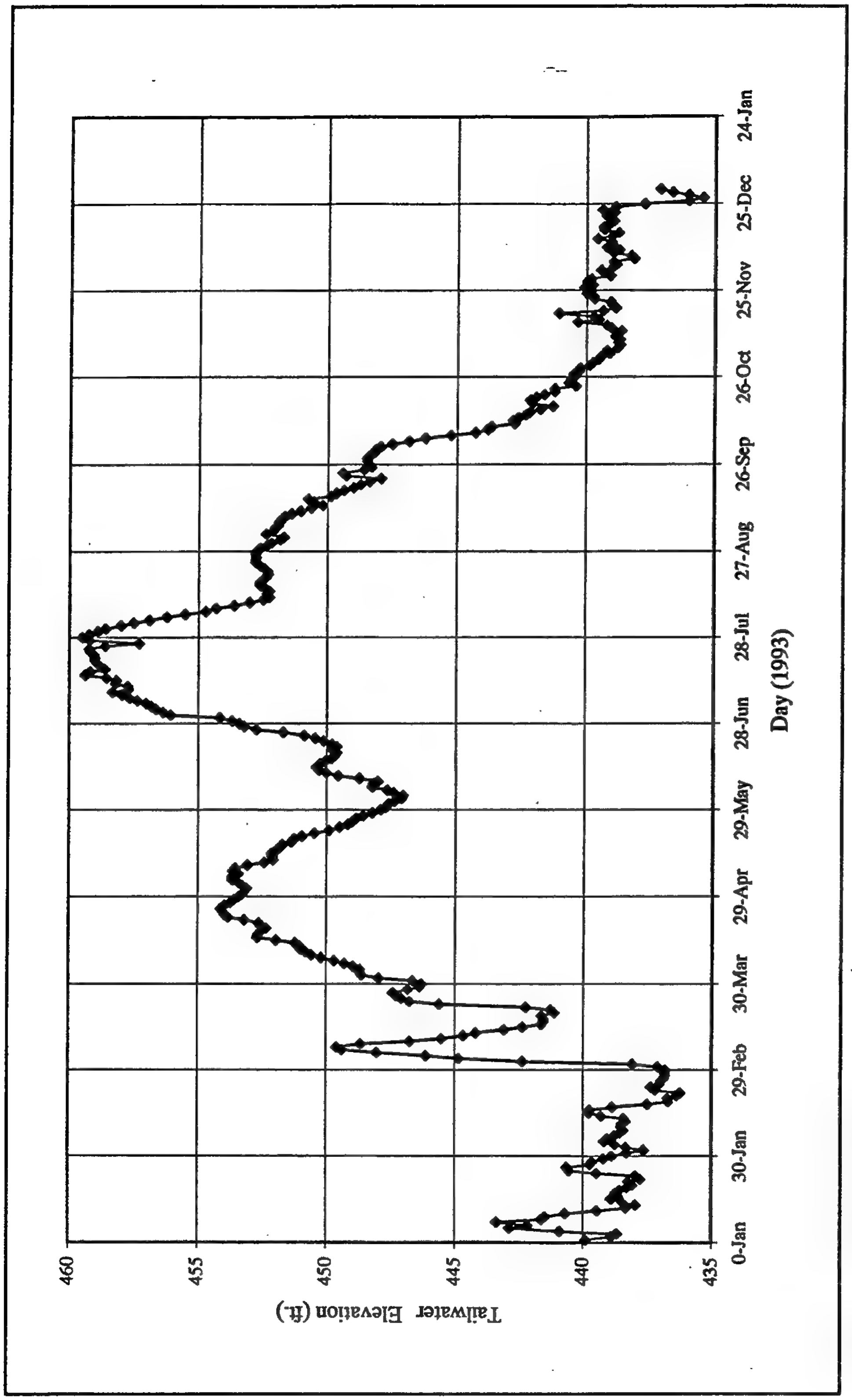


Figure 4b. Tailwater elevations in 1993 for Lock and Dam 24

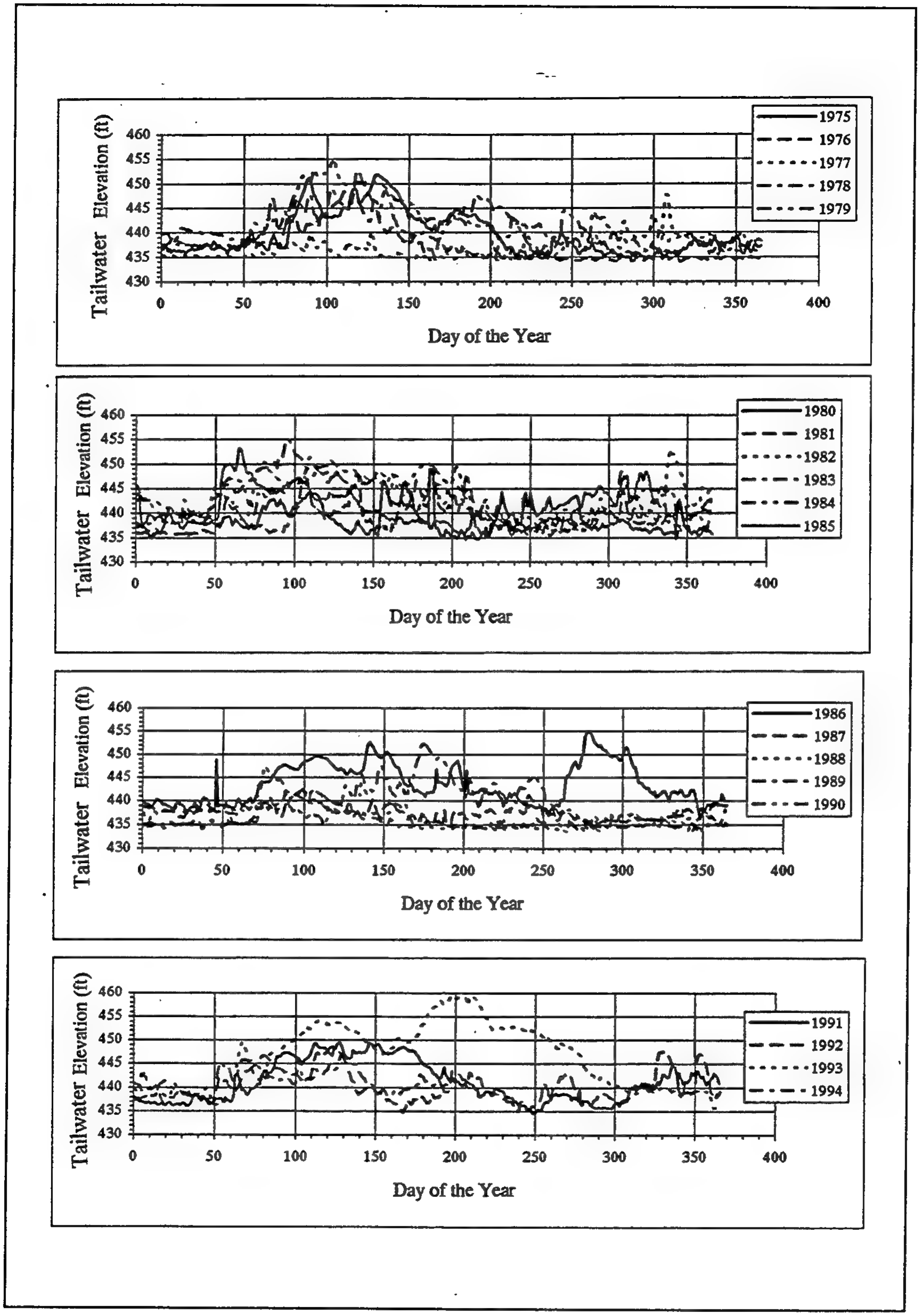


Figure 5a. Tailwater elevations for Lock and Dam 24

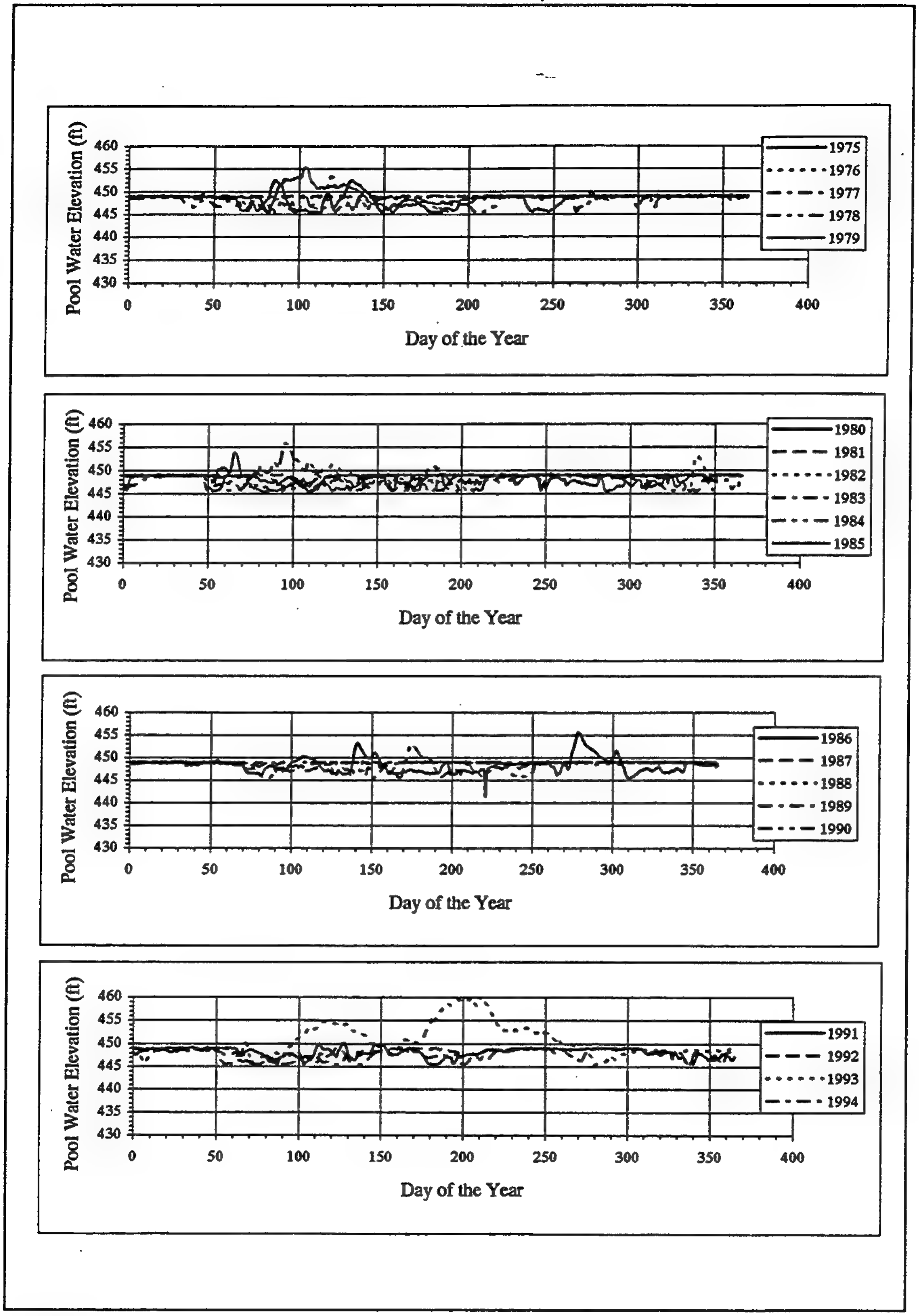


Figure 5b. Pool water elevations for Lock and Dam 24

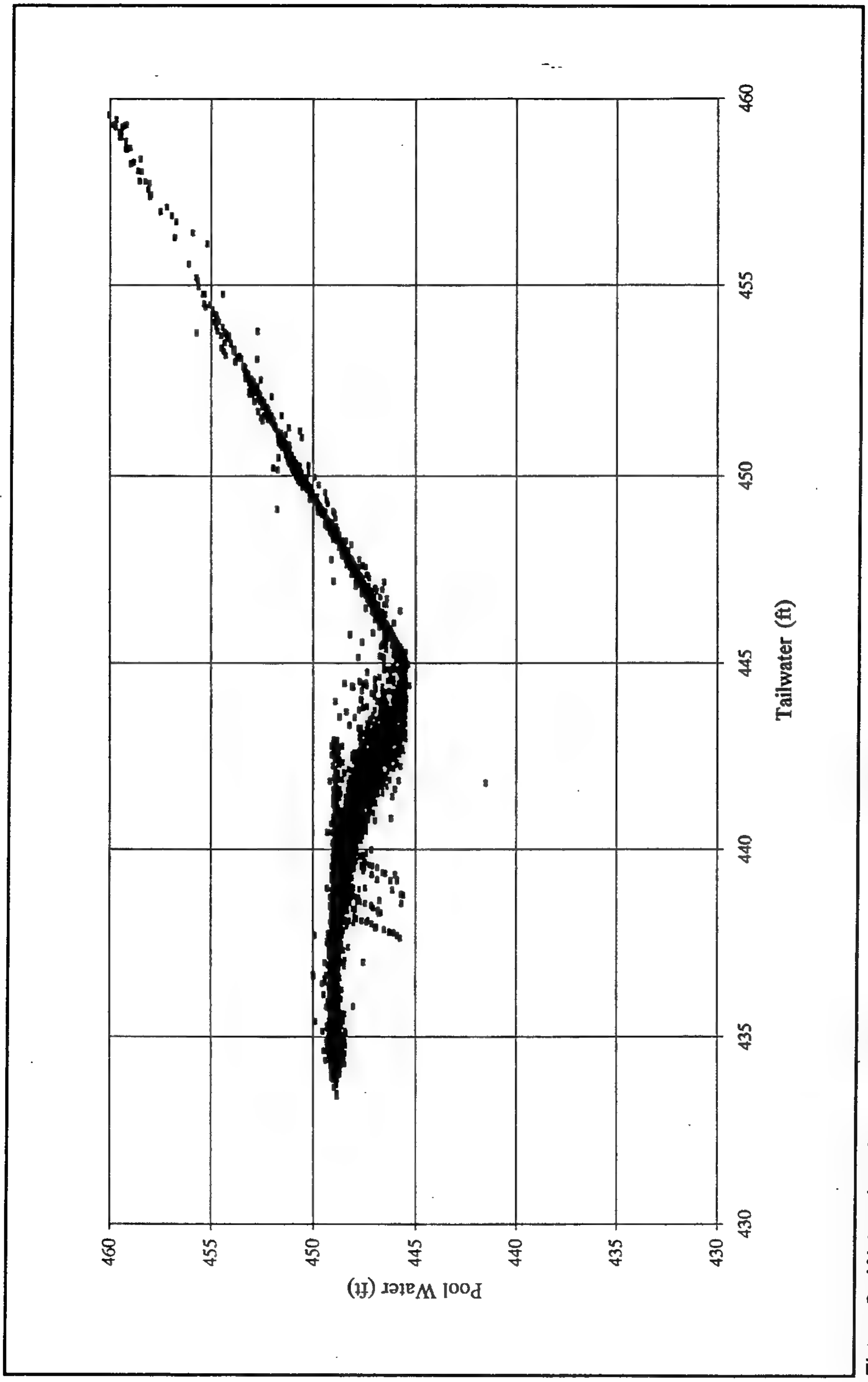


Figure 6. Water elevations for 1975 to 1994 - Lock and Dam 24

Low tailwater elevation

It is observed that the first region can be characterized with a high level of control in maintaining the pool water elevation by the lockmaster. The pool water elevation, in this region, is maintained at a constant level regardless of the tailwater elevation. Correlation analyses of pool and tailwater elevations show that the correlation level is not significant. Based on the hydraulic record, statistical characteristics of the pool water elevation in this region were computed. The mean pool water elevation is 448.89 ft, and the standard deviation is 0.26 ft. The sample size for this region is 3579, which gives a standard error of 0.0044. The maximum and minimum pool water elevations are 449.98 and 445.57 ft, respectively. The resulting model is shown in Figure 7.

Medium tailwater elevation

The region of medium tailwater elevation shows some correlation with pool water elevation as shown in Figure 6. Therefore, linear regression analysis was performed resulting in a correlation coefficient of -0.858. The following linear prediction model of pool water elevation was developed for this region for Lock and Dam 24:

$$H_p = (-0.5531396 \pm 0.0068267) H_t + (691.72094 \pm 3.01333) \tag{55}$$

for $439 \leq H_t < 445.062$ ft)

where H_p is the predicted value of H_p. Each coefficient in the model is provided with its $\pm$ standard error. The standard error of estimates for the model is 0.5611723 based on a sample size in this region of 2356. Both the slope and the intercept in Equation 55 are statistically significant. The resulting model is shown in Figure 7.

High tailwater elevation

The region of high tailwater elevation shows strong correlation with pool water elevation as shown in Figure 6. Therefore, linear regression analysis was performed resulting in a correlation coefficient of 0.996. The following linear prediction model of pool water elevation was developed for this region for Lock and Dam 24:

$$H_p = (1.00118 \pm 0.00001525) H_t \qquad \text{for } H_t \geq 445.062 \text{ ft} \tag{56a}$$

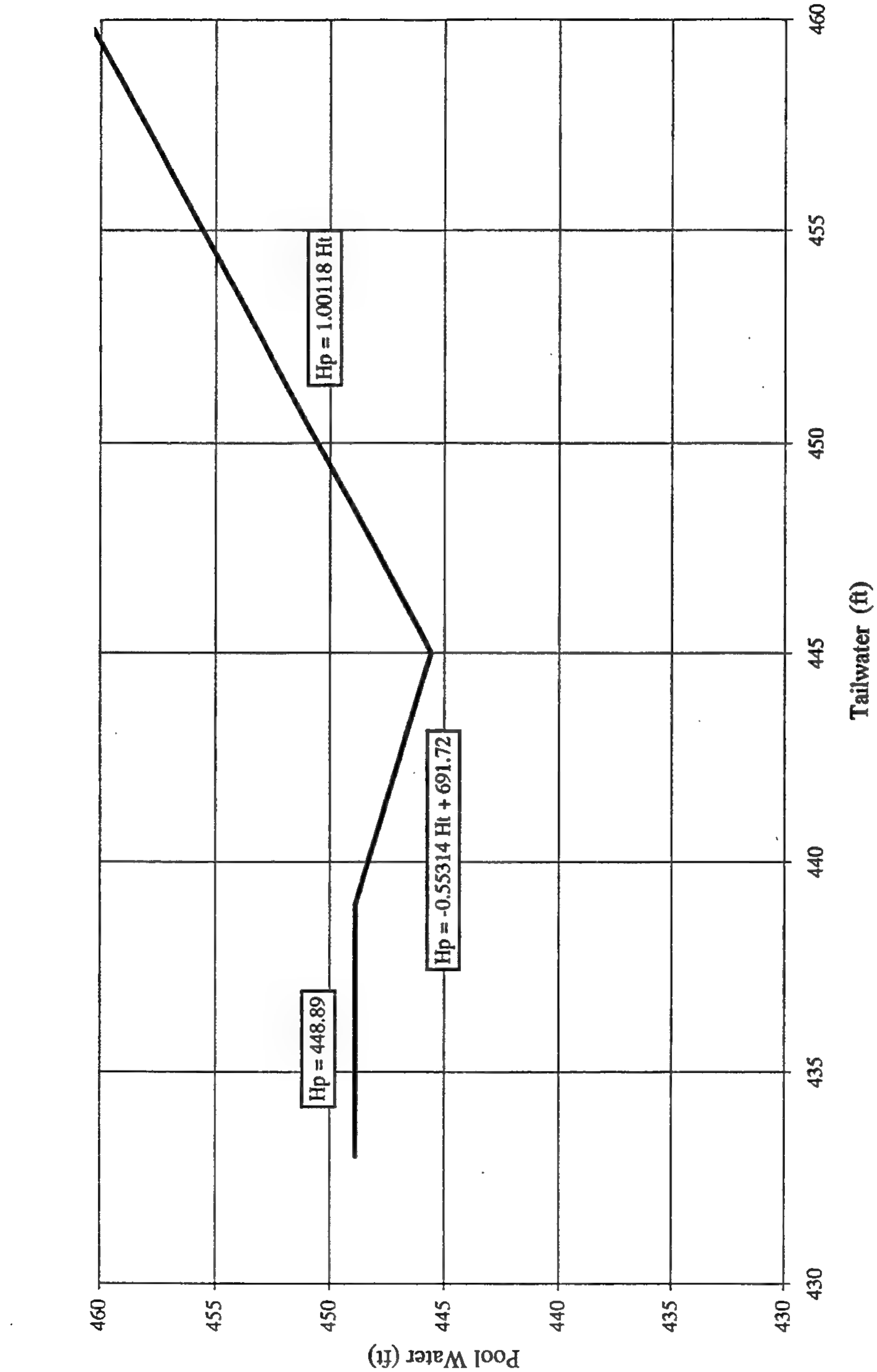


Figure 7. Model for water elevations for 1975 to 1994 - Lock and Dam 24

The slope coefficient in the model is provided with its ± standard error. The intercept for this model was determined to be 0. The standard error of estimates for the model is 0.23762 based on a sample size in this region of 1207. The resulting model is shown in Figure 7, which can be expressed as

$$H_p = \begin{cases} 448.89 \pm 0.0044 & H_t < 439\,ft \\ (-0.5531396 \pm 0.0068267)H_t + (691.72094 \pm 3.01333) & 439 \le H_t < 445.062\,ft \\ (1.00118 \pm 0.00001525)H_t & H_t \ge 445.062\,ft \end{cases} \qquad (56b)$$

The design pool and tailwater elevations are 449.0 ft and 438.6 ft, respectively. Equation 56b can be normalized with respect to the design pool and tailwater elevations to obtain the normalized pool water elevation (H_{pn}) as a function of the normalized tailwater elevation (H_{tn}) as follows:

$$H_{pn} = \begin{cases} 0.999755 \pm 0.0000097 & H_{tn} < 1.000912 \\ (-0.5403274 \pm 0.0066685)H_{tn} + (1.5405812 \pm 0.0067112) & 1.000912 \le H_{tn} < 1.0147332\,ft \\ (0.97799 \pm 0.0000148)H_{tn} & H_{tn} \ge 1.0147332\,ft \end{cases} \qquad (56c)$$

where the normalized pool and tailwater elevations are given, respectively, by

$$H_{pn} = \frac{H_p}{449.0} \qquad (56d)$$

and

$$H_{tn} = \frac{H_t}{438.6} \qquad (56e)$$

Hardware Cycles

The computations of the daily hardware cycles were based on the data obtained from the LPMS and use of the method described in Chapter 4. The daily hardware cycles were computed and adjusted for ice hardware cycles. The adjusted daily hardware cycles are shown in Appendix A. The adjustment for the ice lockages was based on time-lapsed videotapes in the winter months of 1993-1994 for Lock and Dam 22 and Lock and Dam 25 (Patev 1995). The videotapes showed 63 and 75 ice lockages, respectively, over periods of 77 and 65 days, respectively. Therefore, one ice lockage per day was assumed and added to the computed lockage cuts from the LPMS for the months of January and February of each year. Similarly, one ice hardware cycle per day was assumed and added to the computed hardware cycles from the LPMS for the months of January and February of each year.

Using the definition of a lockage cut as the process of passing one cut of a vessel or several vessels through a lock, the number of lockage cuts on monthly and yearly bases are shown in Table 6. The number of hardware cycles on a daily basis, and on monthly and yearly bases corrected for ice lockages are shown in Appendix A and Table 7, respectively. The number of lockage cuts are shown in Figures 8 and 9 on monthly and yearly bases. The number of hardware cycles are also shown in Figures 10 and 11 on monthly and yearly bases. The number of hardware cycles are shown in Figure 12 on a daily basis. These figures indicate the monthly, seasonal, and yearly variations of these quantities. The intention behind developing these plots was to investigate the need of developing hardware-cycle histograms based on monthly, seasonal, or yearly parameters. However, as described below, the computed small correlation level between water elevation and number of hardware cycles allowed the aggregation of all water-elevation records in one model without regard to monthly, seasonal, or yearly variations.

Tailwater-Hardware Cycles Analysis

The objective in this section is to aggregate the number of hardware cycles that are associated with the same tailwater elevation based on their daily records obtained in the sections above. A graphical correlation analysis between the hardware cycles and tailwater elevation was performed as shown in Figures 13 and 14. The estimated correlation coefficient is 0.155 which is small indicating that all daily records can be aggregated without regard to monthly, seasonal, or yearly variations. The number of hardware cycles that are associated with the same tailwater elevation were aggregated to obtain a histogram as shown in Figures 15 and 16. The histogram values are shown in Table 8. Based on the daily records of

tailwater elevations and the corresponding hardware cycles, a weighted average of water elevation was computed to be 440.685 ft. The total number of cycles in the entire period is 150,938. The standard deviation of the weighted tailwater elevation is 4.5817 ft. The maximum and minimum tailwater elevations are 453.71 and 433.34, respectively.

Table 6
Summary of Lockages from 1980 to 1994 for Lock and Dam 24

(Assumption: Add one ice cycle per day during Jan and Feb for all years)
(A lockage is the process to pass through one cut of a vessel, or more than one vessel)

Month	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994
January	124	117	120	164	110	90	114	104	90	57	136	106		132	68
February	84	102	81	138	286	71	88	99	92	51	234	123	34	105	94
March	346	566	419	481	608	433	374	447	560	452	685	555	710	466	
April	606	706	651	493	790	589	483	604	761	726	772	740	777	390	
May	602	723	810	695	690	541	515	743	840	789	878	754	836	627	
June	673	697	718	745	630	501	554	682	710	803	806	743	814	657	
July	766	667	669	847	638	614	577	797	766	871	954	899	977		
August	859	803	785	833	691	559	676	838	823	732	886	857	893	241	
September	841	698	643	819	613	532	583	709	771	707	752	691	709	674	
October	765	625	497	810	604	448	426	700	776	704	689	693	566	654	
November	685	699	602	793	686	523	648	568	683	690	676	642	538		
December	304	385	324	290	249	198	224	232	259	205	275	160	263	243	
TOTAL	6655	6788	6319	7108	6595	5099	5262	6523	7131	6787	7743	6963	7117	4189	162

Table 7
Summary of Hardware Cycles from 1980 to 1994 for Lock and Dam 24

(Assumption: Add one ice cycle per day during Jan and Feb for all years)

Month	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994
January	179	161	165	234	133	109	146	145	128	63	191	133		189	88
February	96	153	97	201	464	86	116	139	124	54	351	172	9	146	128
March	585	968	711	835	1052	740	633	776	970	788	1181	970	1236	811	
April	1023	1217	1122	893	1346	1008	830	1015	1293	1223	1335	1276	1347	675	
May	1003	1220	1347	1191	1180	901	882	1251	1405	1309	1545	1264	1420	1122	
June	1115	1157	1222	1252	1057	839	899	1124	1175	1330	1415	1233	1383	1120	
July	1250	1113	1100	1429	1075	976	936	1302	1220	1410	1589	1438	1632		
August	1379	1328	1315	1495	1164	928	1078	1404	1323	1207	1447	1352	1486	421	
September	1387	1155	1064	1461	1013	872	930	1181	1261	1175	1201	1146	1128	1166	
October	1257	1046	844	1413	1026	746	758	1169	1287	1165	1176	1134	937	1110	
November	1158	1175	1015	1354	1173	886	1100	970	1142	1171	1155	1126	918		
December	511	647	552	481	419	319	368	389	431	341	466	276	443	410	
TOTAL	10943	11340	10554	12239	11102	8410	8676	10865	11759	11236	13052	11520	11939	7170	216

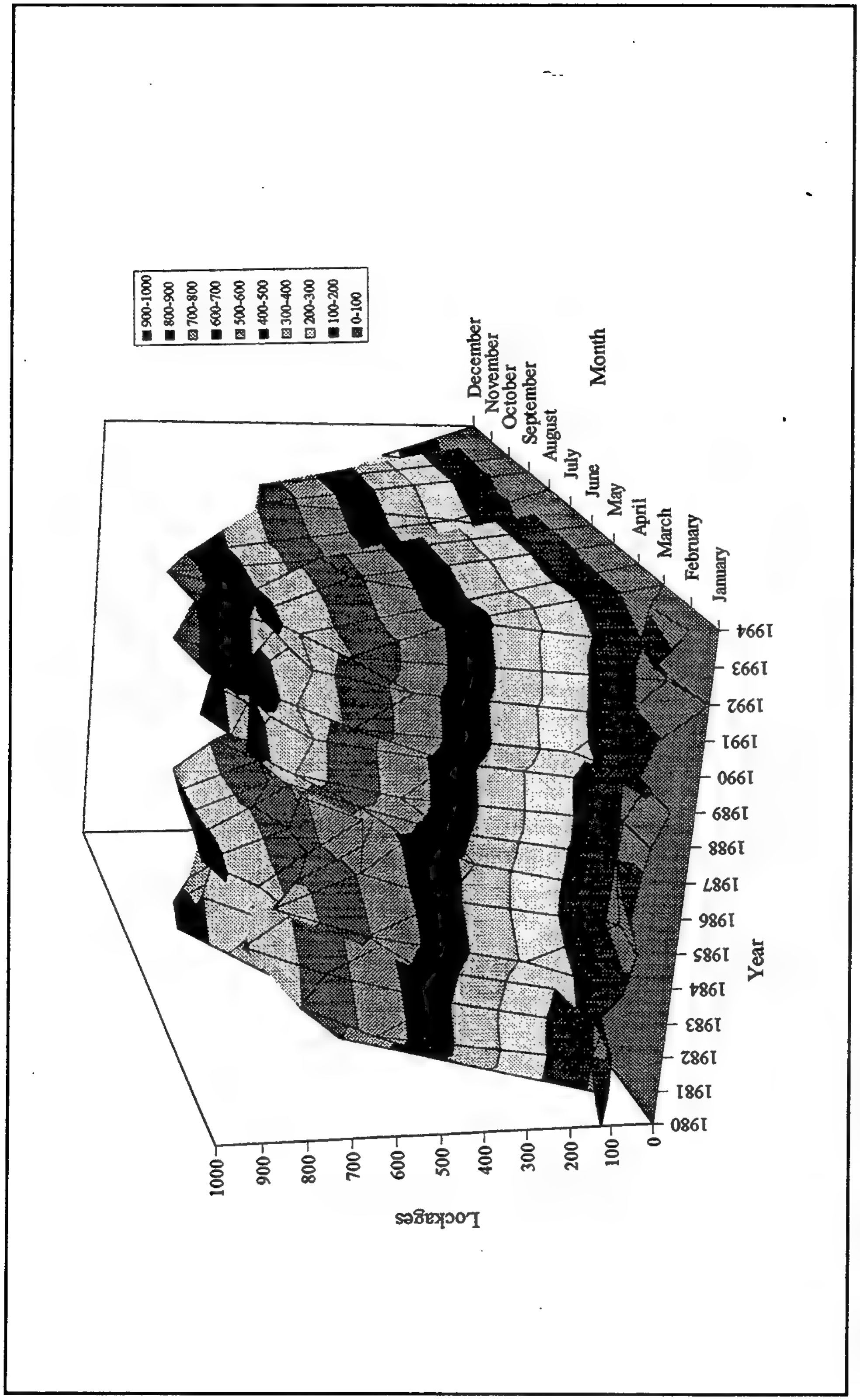


Figure 8. Summary (3-dimensional) of lockages for 1980 to 1994 - Lock and Dam 24

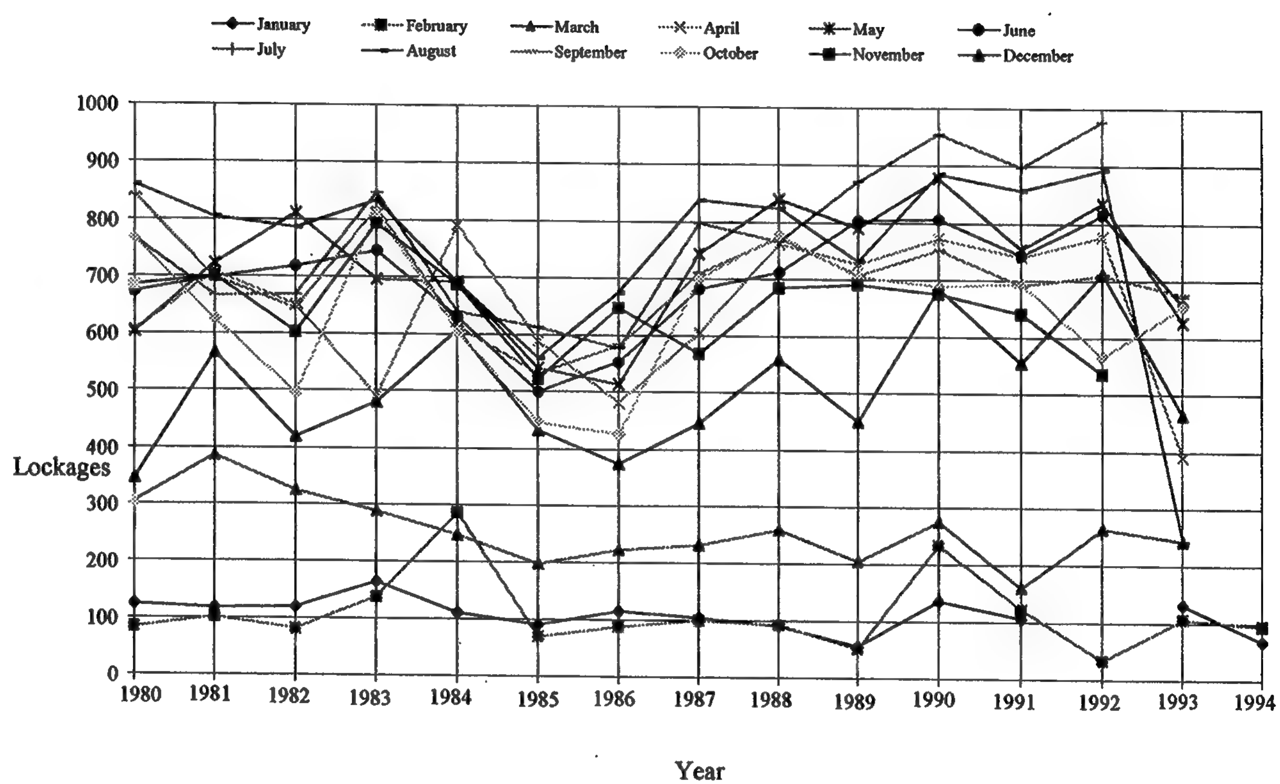


Figure 9. Summary (2-dimensional) of lockages for 1980 to 1994 - Lock and Dam 24

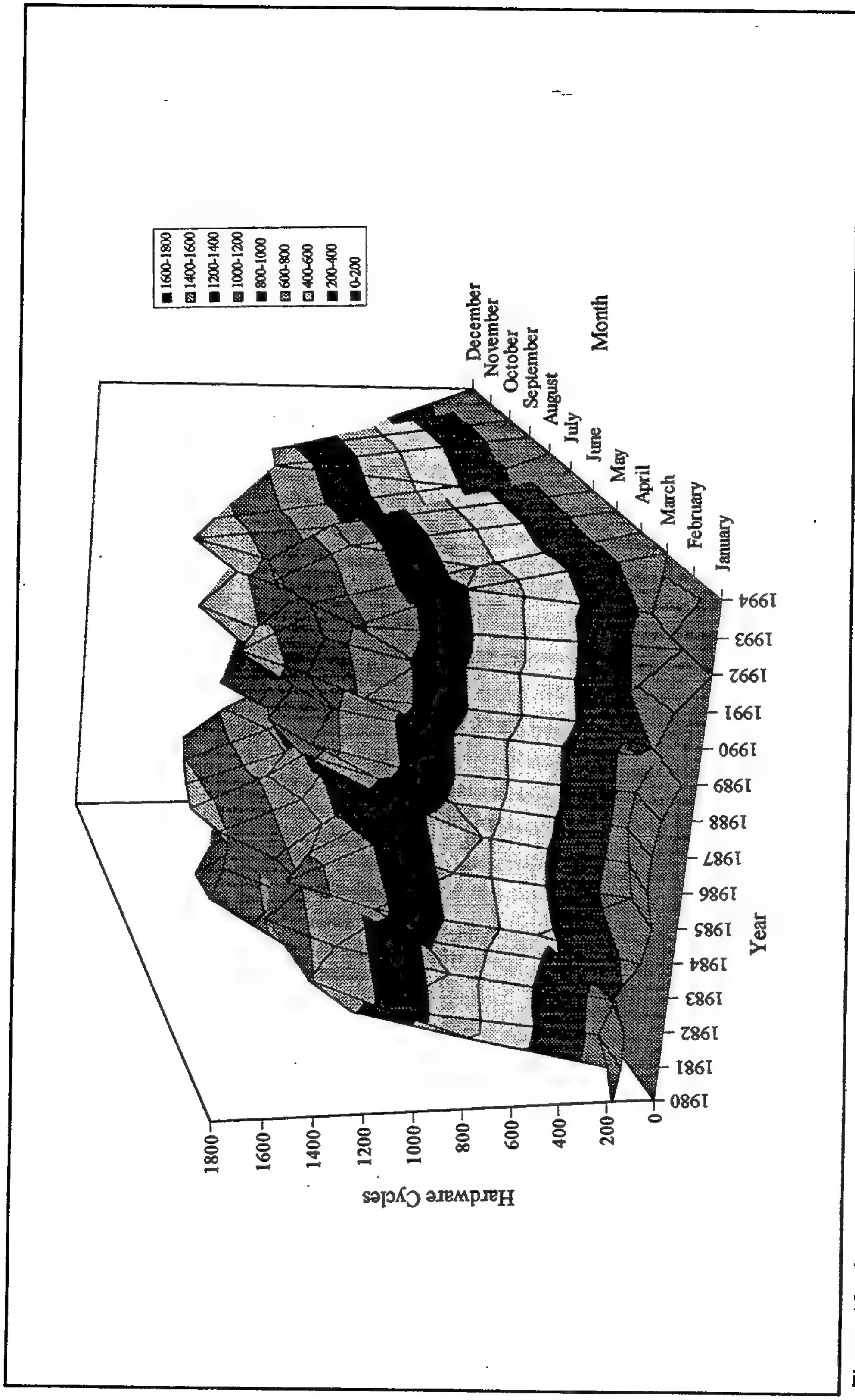


Figure 10. Summary (3-dimensional) of hardware cycles for 1980 to 1994 - Lock and Dam 24

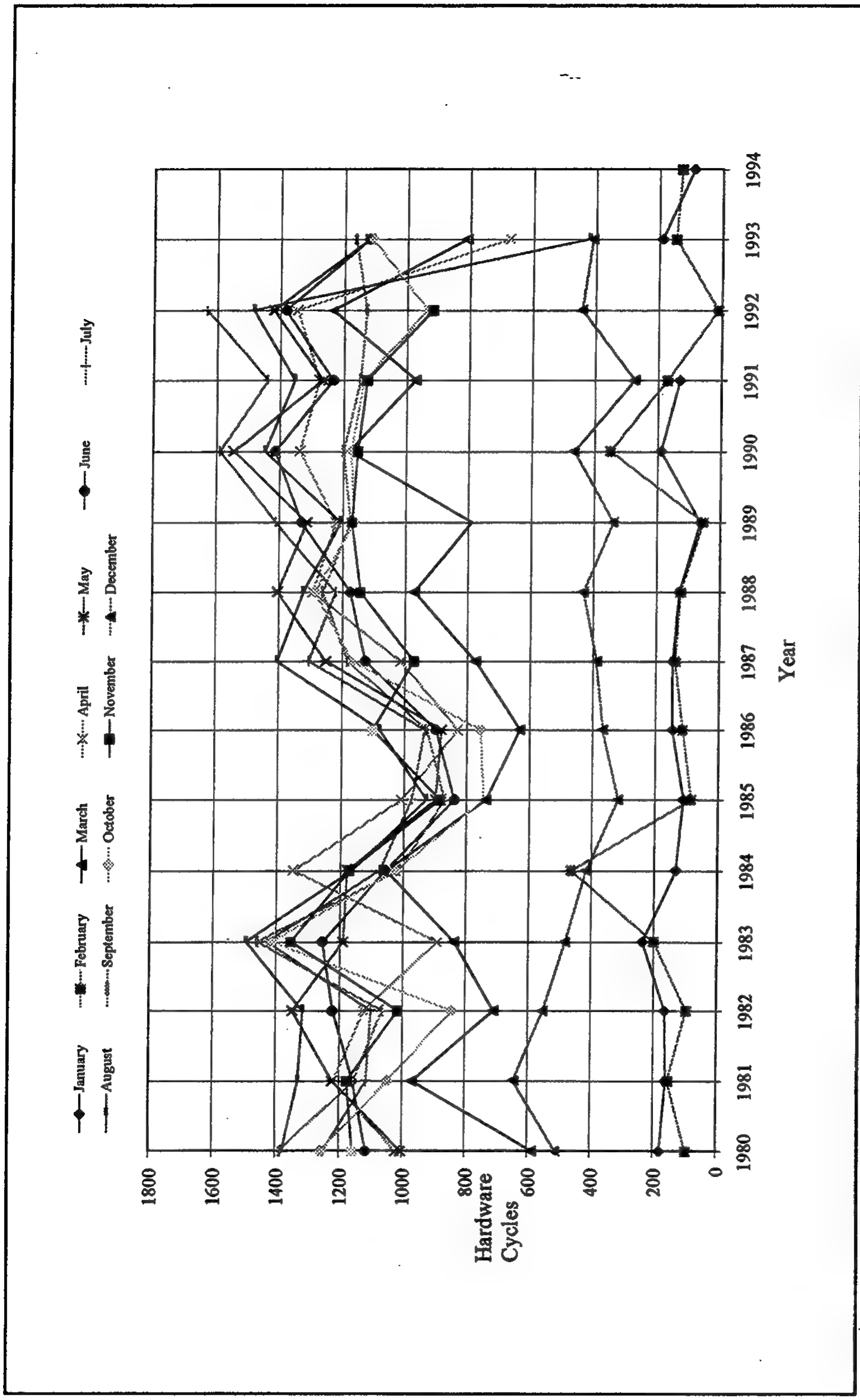


Figure 11. Summary (2-dimensional) by month of hardware cycles for 1980 to 1994 - Lock and Dam 24

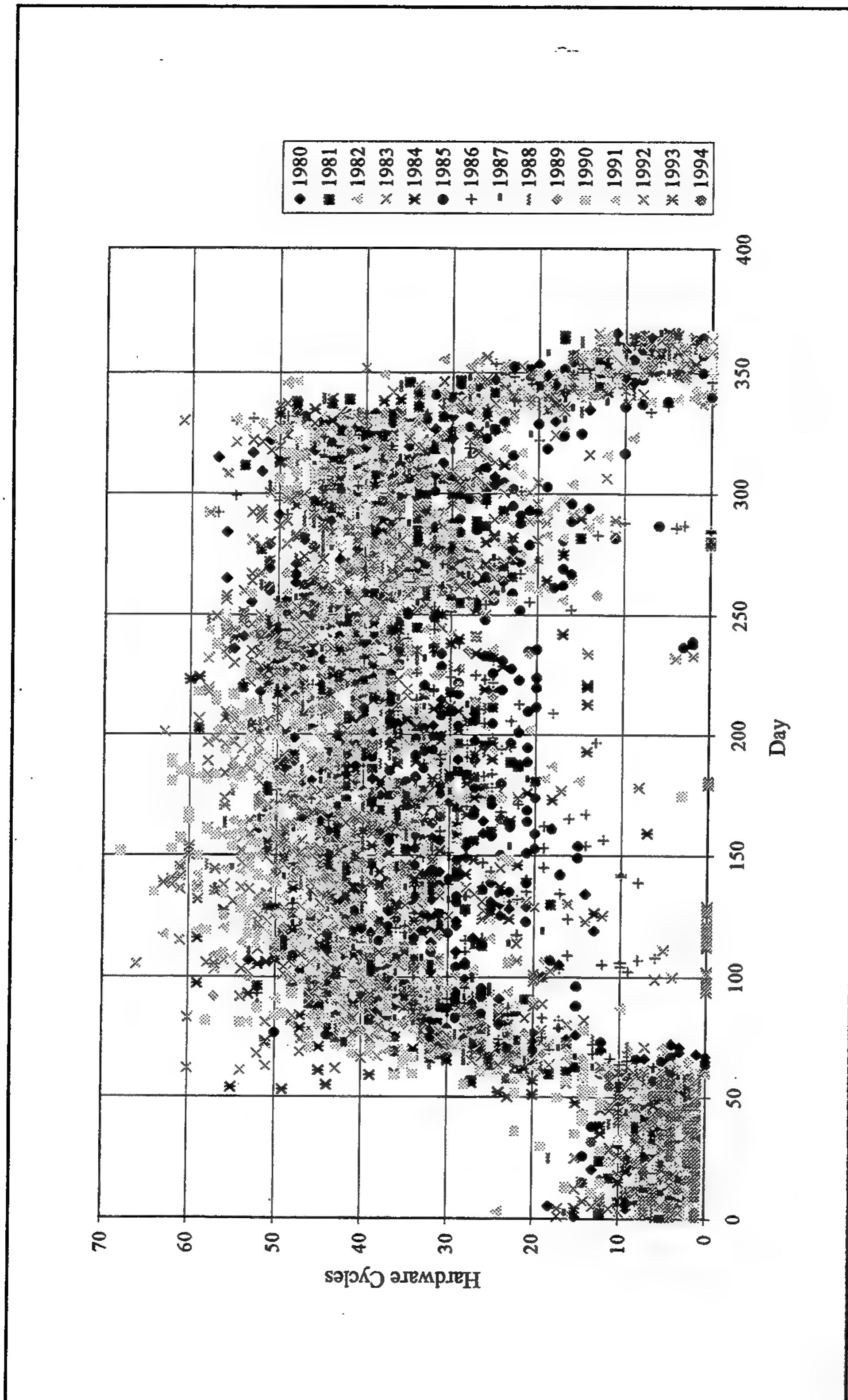


Figure 12. Summary (2-dimensional) by year of hardware cycles for 1980 to 1994 - Lock and Dam 24

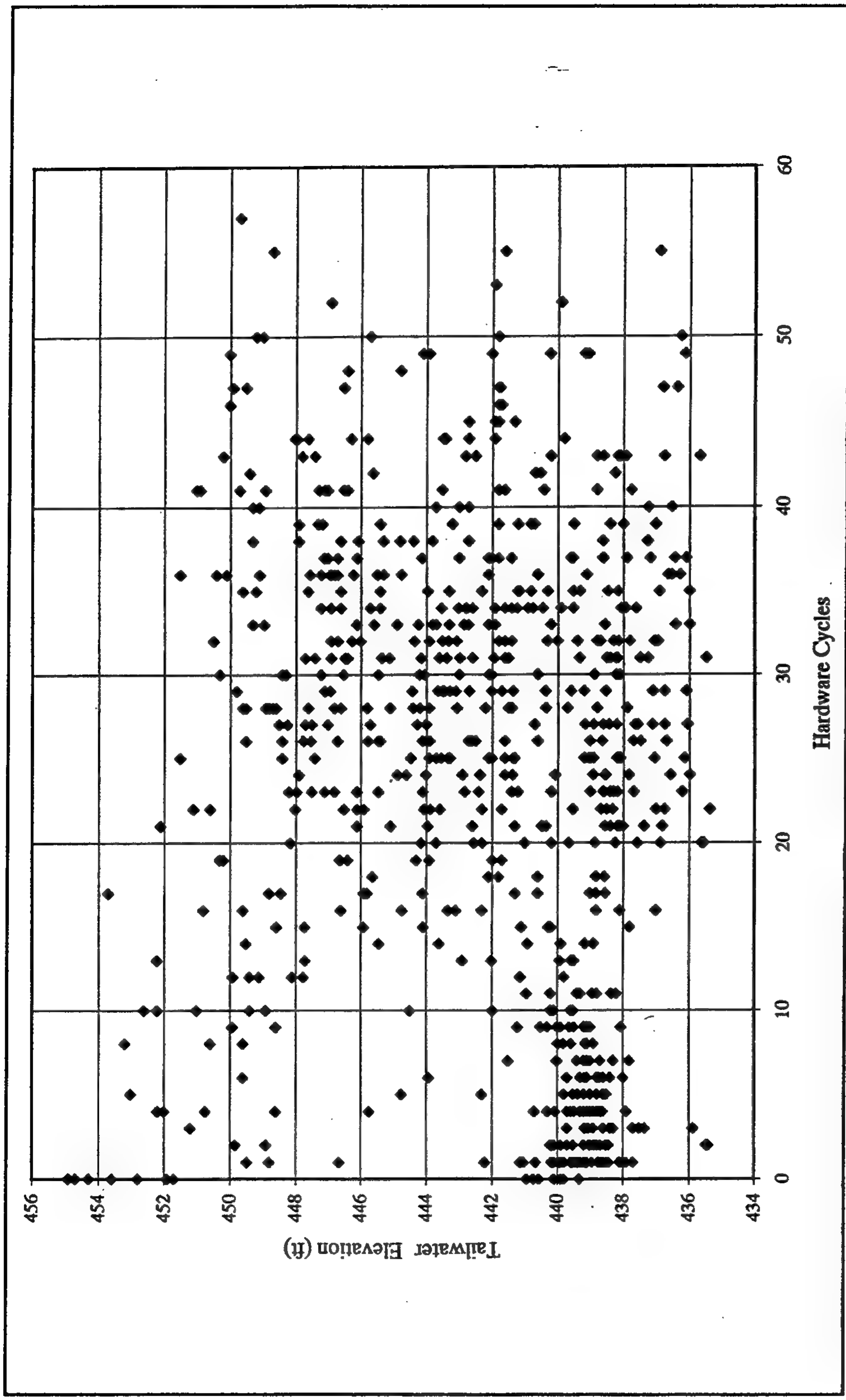
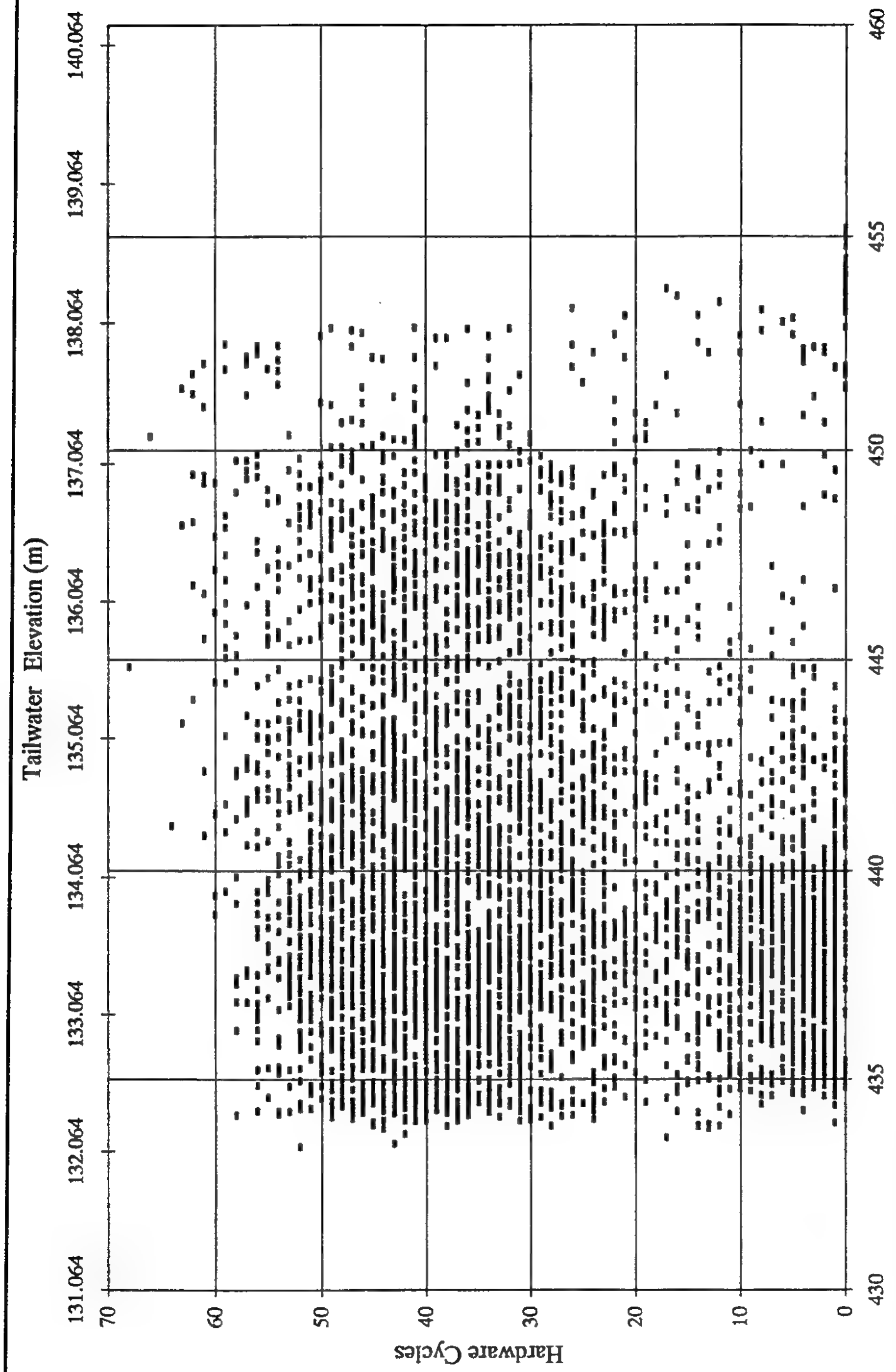


Figure 13. Daily tailwater elevation and hardware cycles for 1985 and 1986 - Lock and Dam 24



Correlation Coefficient = 0.155

Figure 14. Daily tailwater elevation and hardware cycles for 1980 to 1994 - Lock and Dam 24

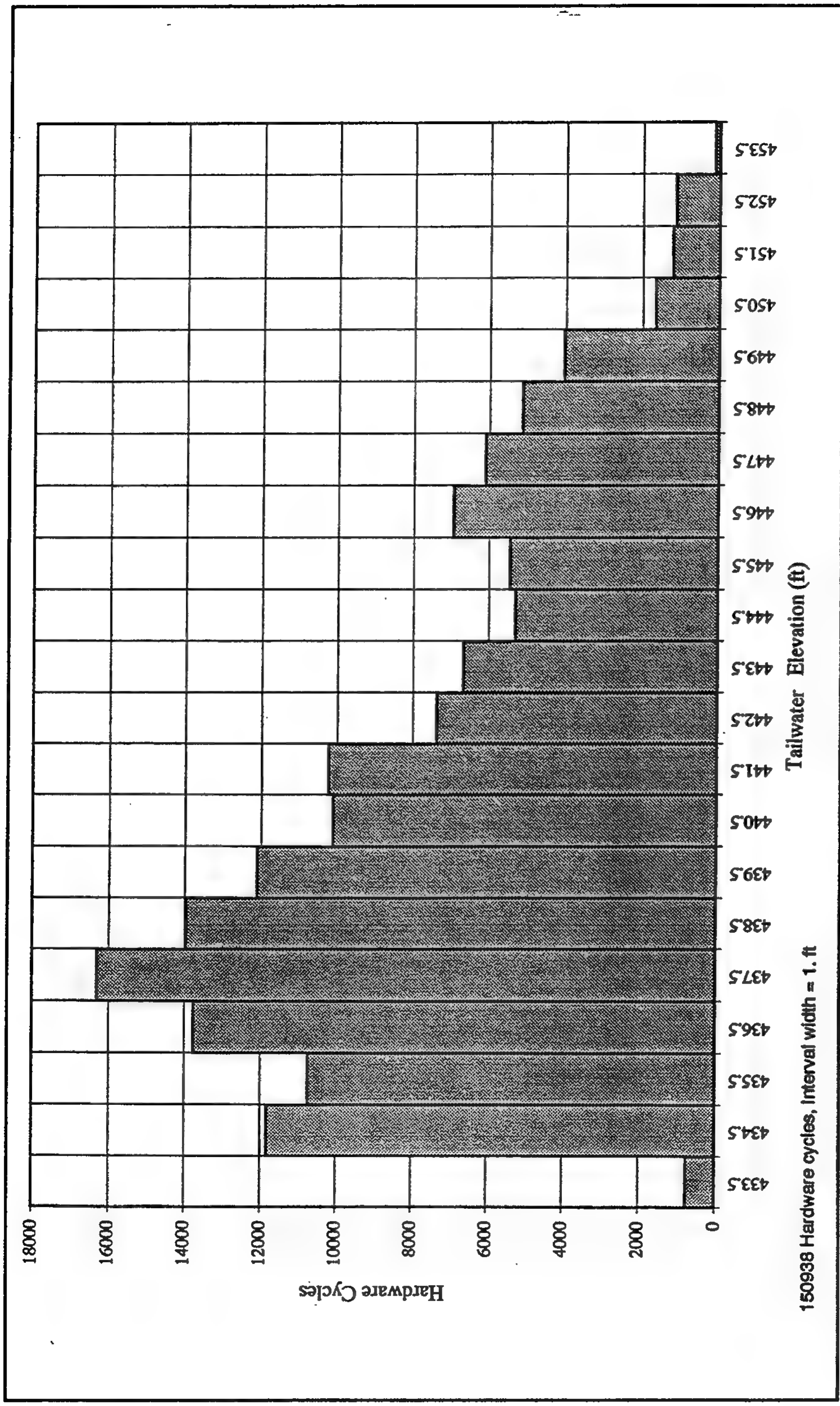


Figure 15. Histogram of tailwater elevation and hardware cycles for Lock and Dam 24

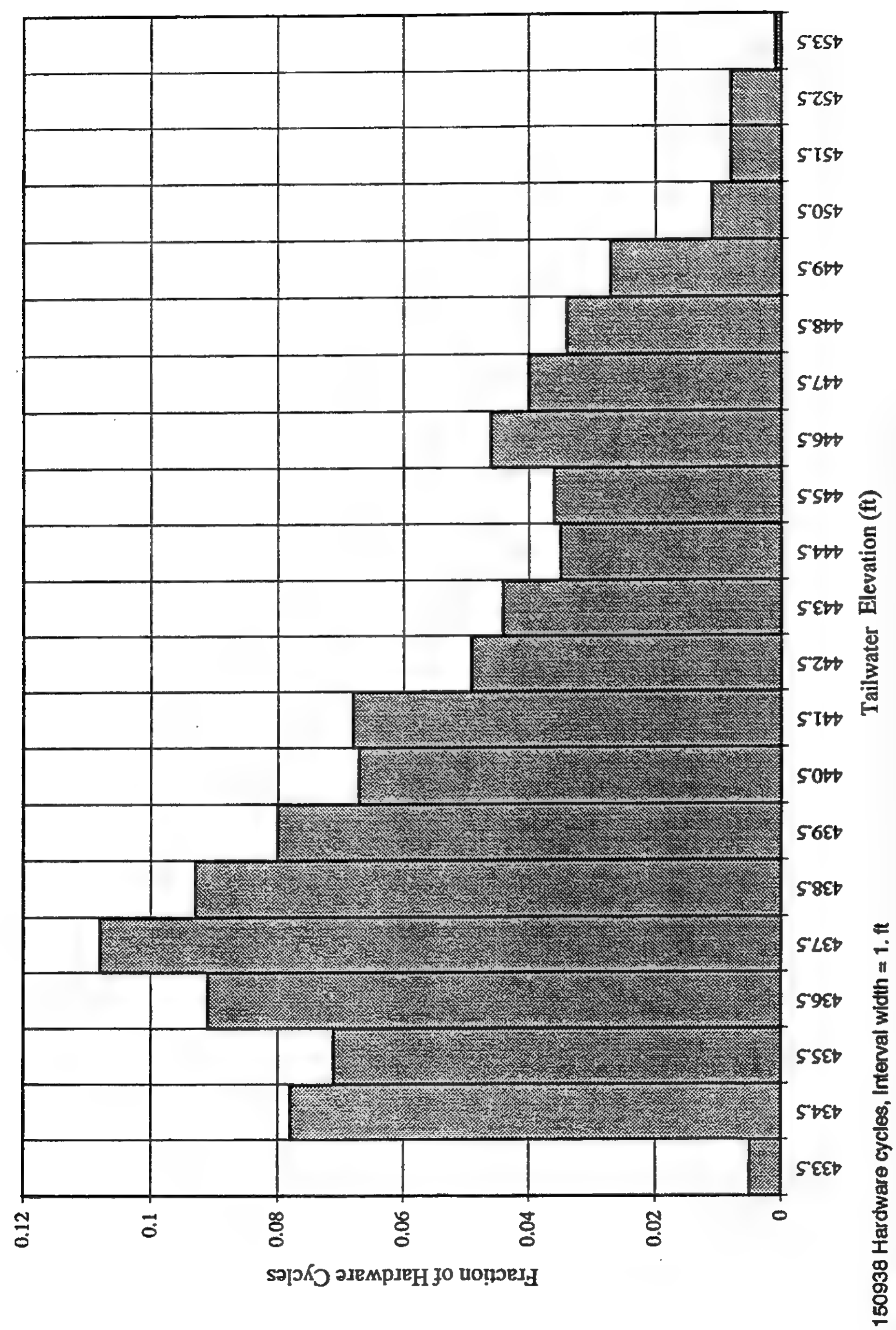


Figure 16. Histogram of tailwater elevation and hardware-cycle fraction for Lock and Dam 24

Table 8
Data for Tailwater Elevation and Hardware Cycles Histogram

Interval Start of Tailwater (ft)	Interval End of Tailwater (ft)	Mid-Interval of Tailwater (ft)	Count of Hardware Cycles	Fraction of Hardware Cycles
430	431	430.5	0	0
431	432	431.5	0	0
432	433	432.5	0	0
433	434	433.5	755	0.005
434	435	434.5	11827	0.078
435	436	435.5	10726	0.071
436	437	436.5	13762	0.091
437	438	437.5	16306	0.108
438	439	438.5	13966	0.093
439	440	439.5	12097	0.08
440	441	440.5	10099	0.067
441	442	441.5	10225	0.068
442	443	442.5	7359	0.049
443	444	443.5	6670	0.044
444	445	444.5	5302	0.035
445	446	445.5	5445	0.036
446	447	446.5	6949	0.046
447	448	447.5	6110	0.04
448	449	448.5	5133	0.034
449	450	449.5	4047	0.027
450	451	450.5	1669	0.011
451	452	451.5	1229	0.008
452	453	452.5	1143	0.008
453	454	453.5	119	0.001
454	455	454.5	0	0
455	456	455.5	0	0
456	457	456.5	0	0
TOTAL			150938	1

The resulting histogram can be used to select a probability distribution model. The normal, lognormal, Weibull, and Gumbel probability distributions were considered as candidate models. The chi-square goodness-of-fit test (Ang and Tang 1984) was used to select the best model among the candidate distributions. Figure 17 shows the histogram with the four candidate distributions. By examining Figure 17, and based on the results of the chi-square test, the Weibull distribution can be considered to be the best model among the candidate ones. The Weibull's cumulative distribution function ($F_{h_t}(h_t)$) for tailwater elevation loading is

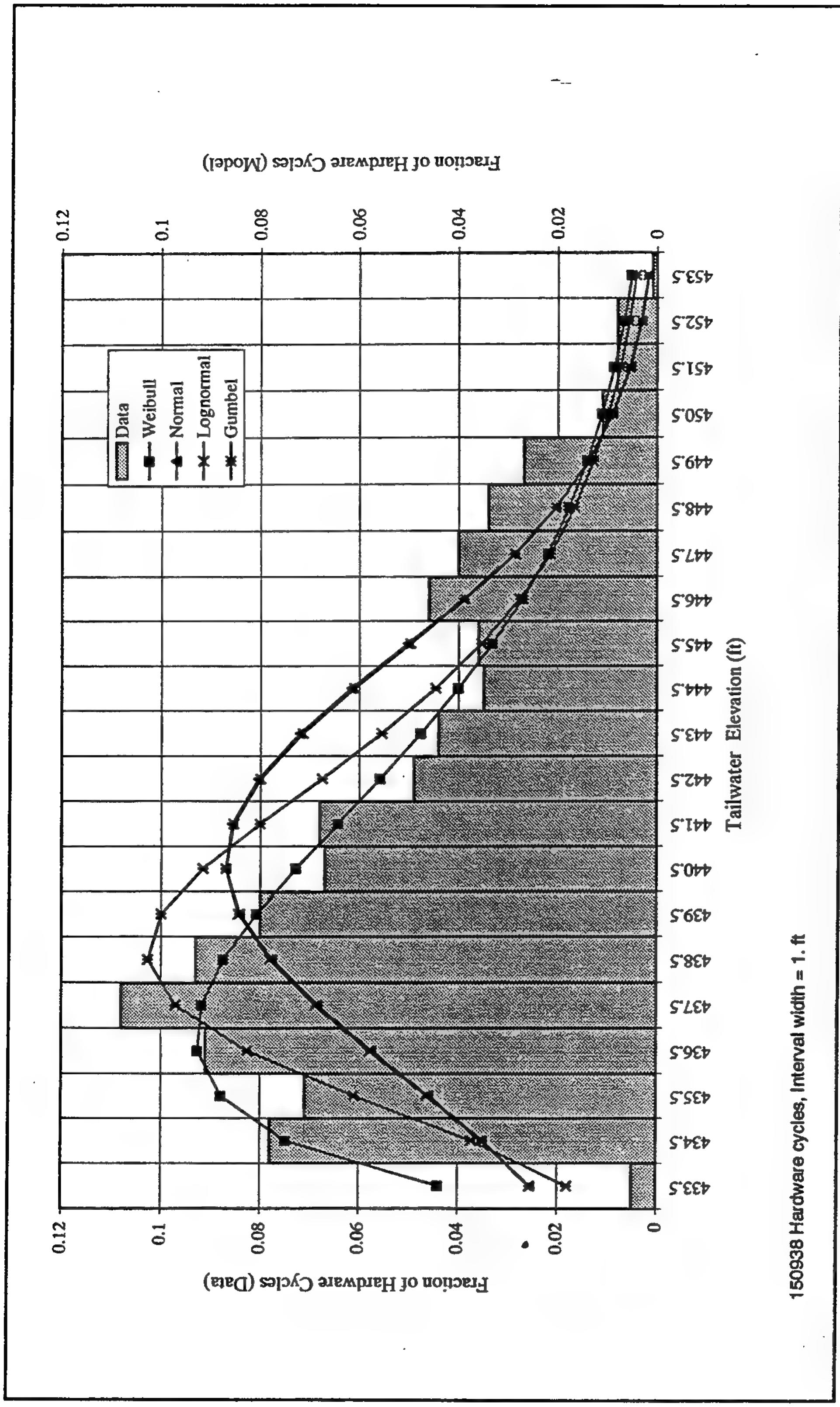


Figure 17. Histogram of tailwater elevation and hardware-cycle fraction with function fits to data for Lock and Dam 24

$$F_{H_t}(h_t) = 1 - \exp\left[-\left(\frac{h_t - H_{t\min}}{(H_{t\max} - H_{t\min})b} \right)^a \right] \tag{57}$$

where H_{tmin} = minimum tailwater elevation which was taken as 433 ft, H_{tmax} = maximum tailwater elevation which was taken as 454 ft, H_t = tailwater elevation loading as a random variable with a given value of h_t, and a (shape) and b (scale) are the parameters of the distribution. The shape (a) and scale (b) parameters were estimated using the best linear invariant estimation (Mann, Shaffer, and Singpurwalla 1974) to be 1.4909 and 0.3812, respectively. The mean and variance based on these parameters are 440.23 ft and 24.329 ft^2, respectively. These moments are approximately equal to the moments computed as the weighted average and variance of tailwater elevation of 440.685 ft and 20.99 ft^2, respectively. Equation 57 can be expressed in terms of the normalized water elevation H_{tn}.

Relationships Among Tonnage, Lockages, Hardware Cycles, and Time

The objective of this section is to study the relationships for Lock and Dam 24 among tonnage, number of lockages, number of hardware cycles, and time. Figures 18, 19, and 20 show the trend of tonnage, lockages, and hardware cycles. Figures 21, 22, and 23 show the trend of the ratio of tonnage to lockages, the ratio of tonnage to hardware cycles, and the ratio of lockages to hardware cycles, respectively. The last set of figures shows the scatter diagrams for the relationships between lockages and tonnage (Figure 24), hardware cycles and tonnage (Figure 25), and hardware cycles and lockages (Figure 26). The relationship between hardware cycles and lockages, the trend relationship of the annual number of lockages, and the relationship between lockages and tonnage were developed. Then, a tonnage forecast model was developed based on data obtained using the GEM (USACE 1994) for Lock and Dam 24.

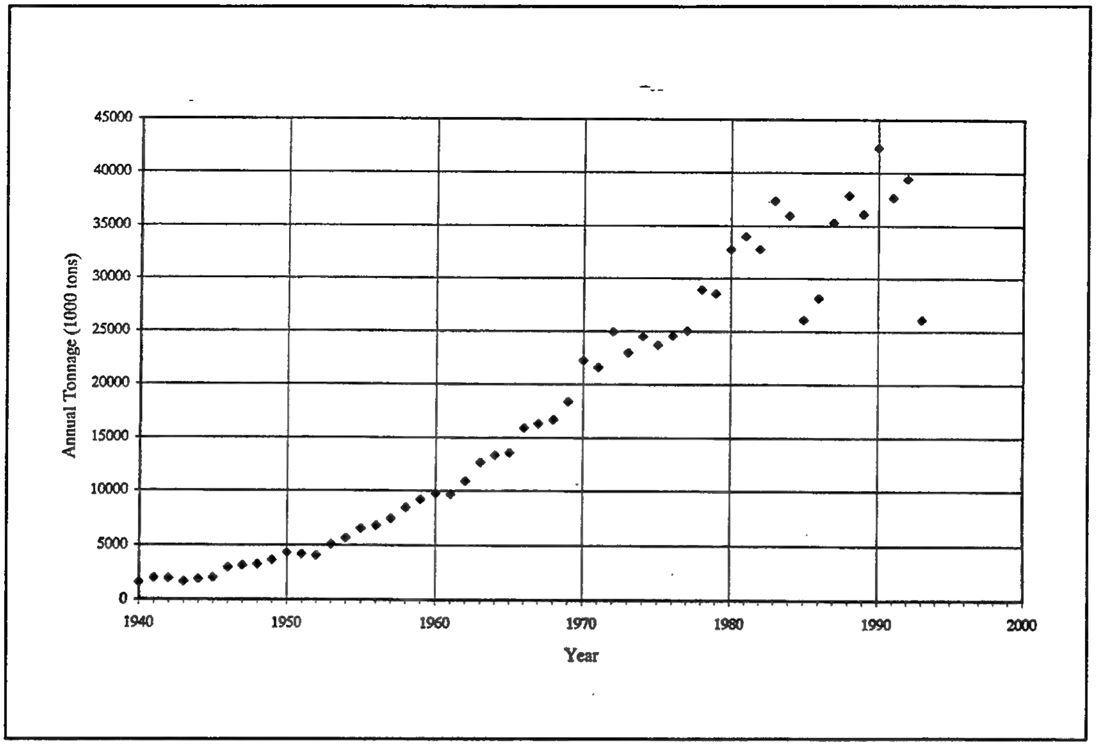


Figure 18. Tonnage trend for Lock and Dam 24

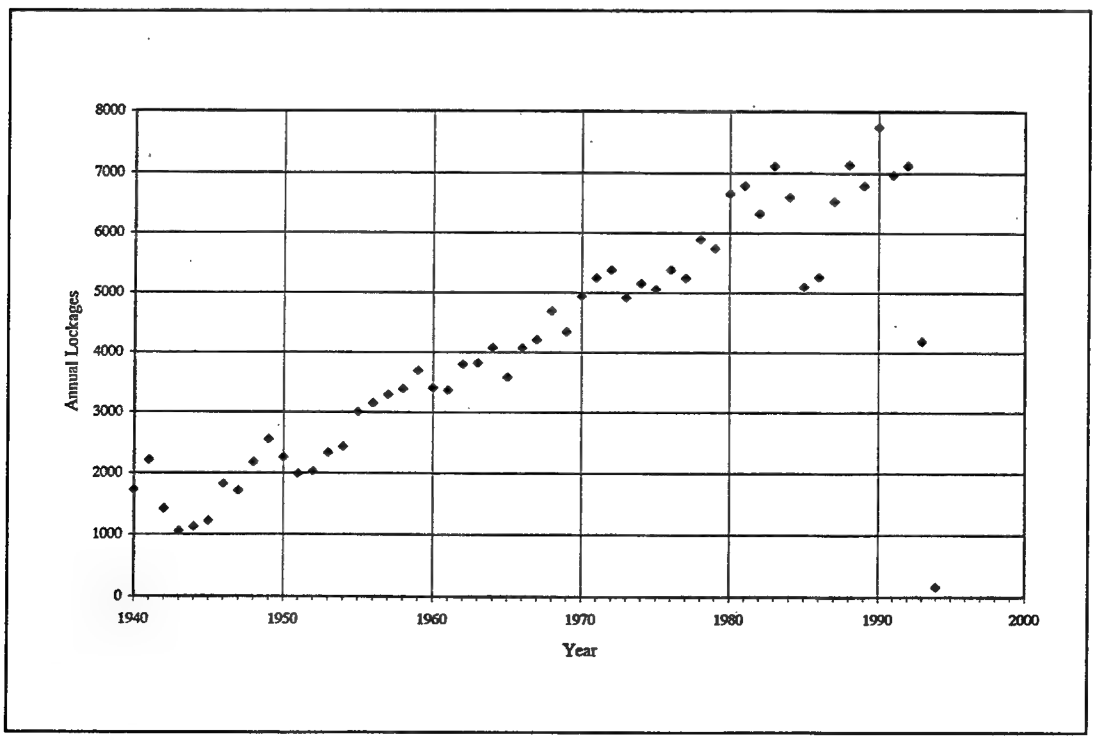


Figure 19. Trend of lockages for Lock and Dam 24

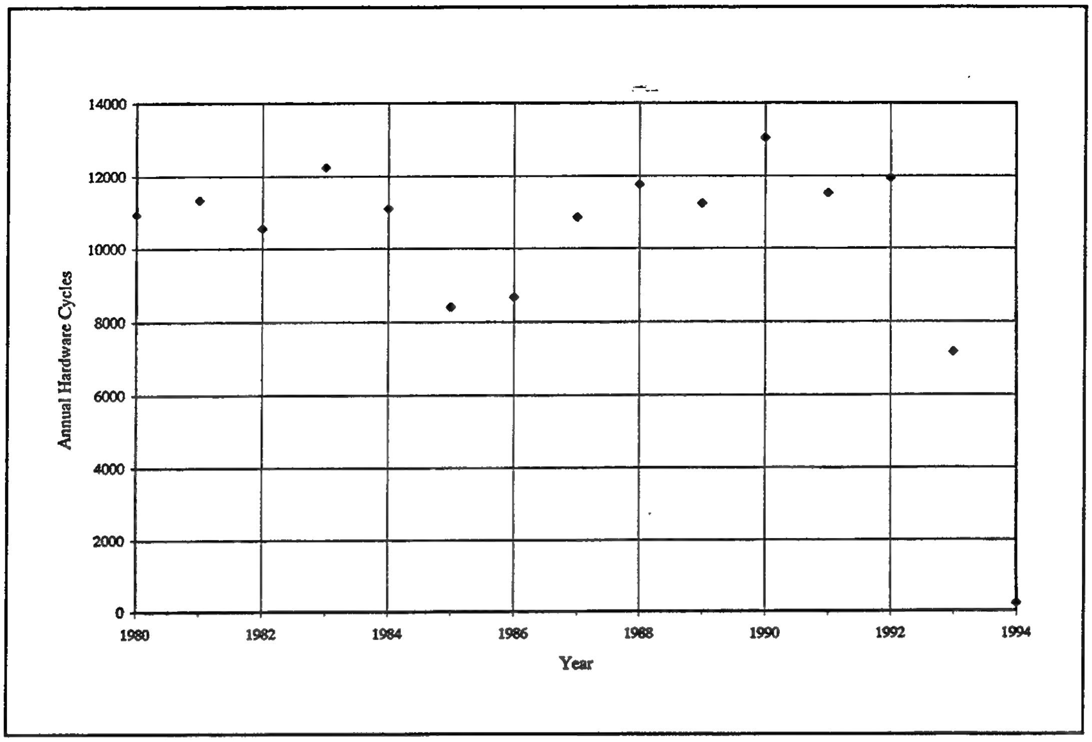


Figure 20. Trend of hardware cycles for Lock and Dam 24

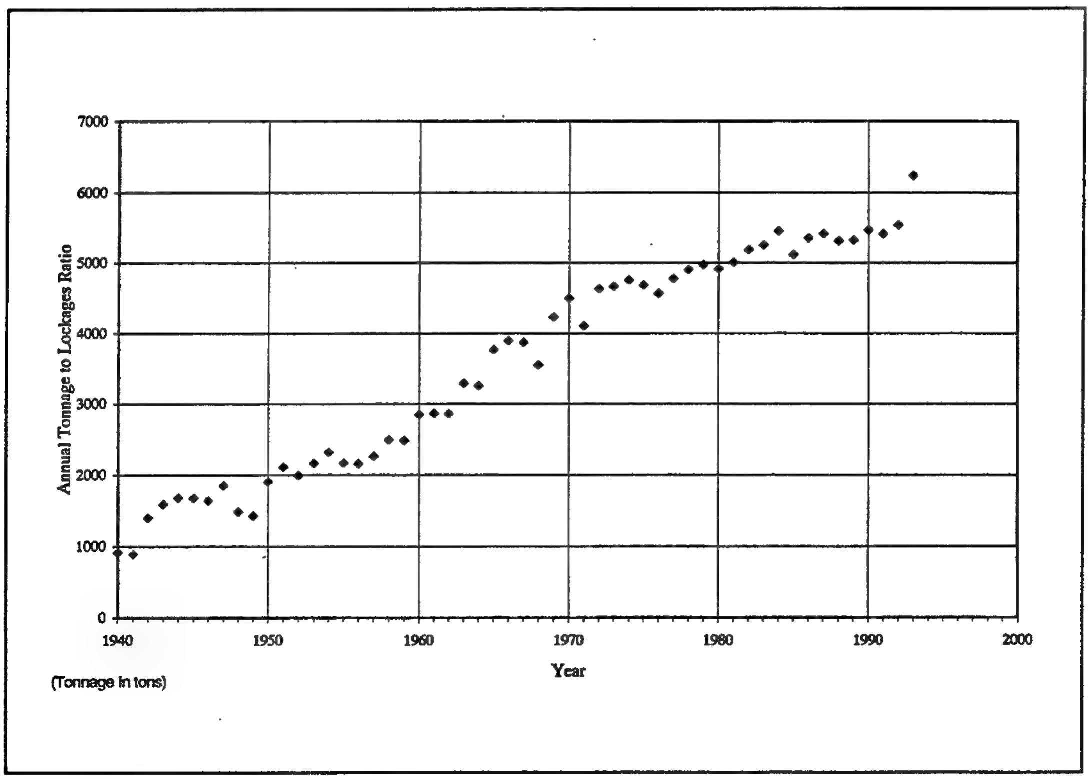


Figure 21. Trend of the ratio of tonnage to lockages for Lock and Dam 24

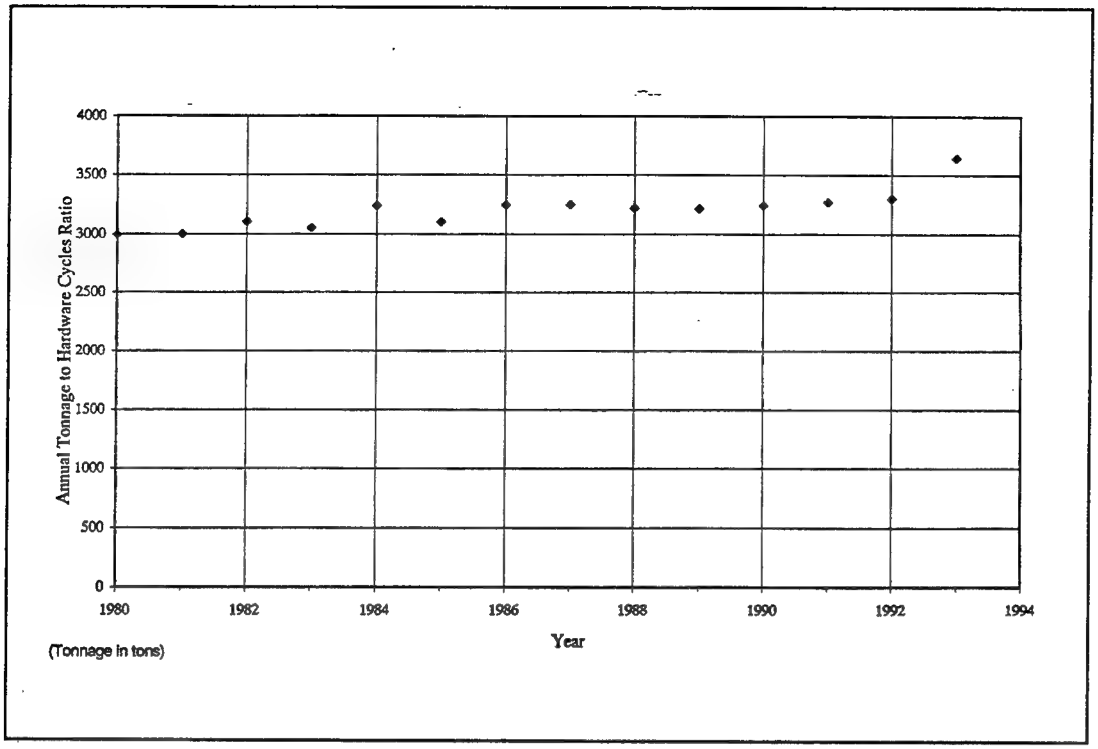


Figure 22. Trend of the ratio of tonnage to hardware cycles for Lock and Dam 24

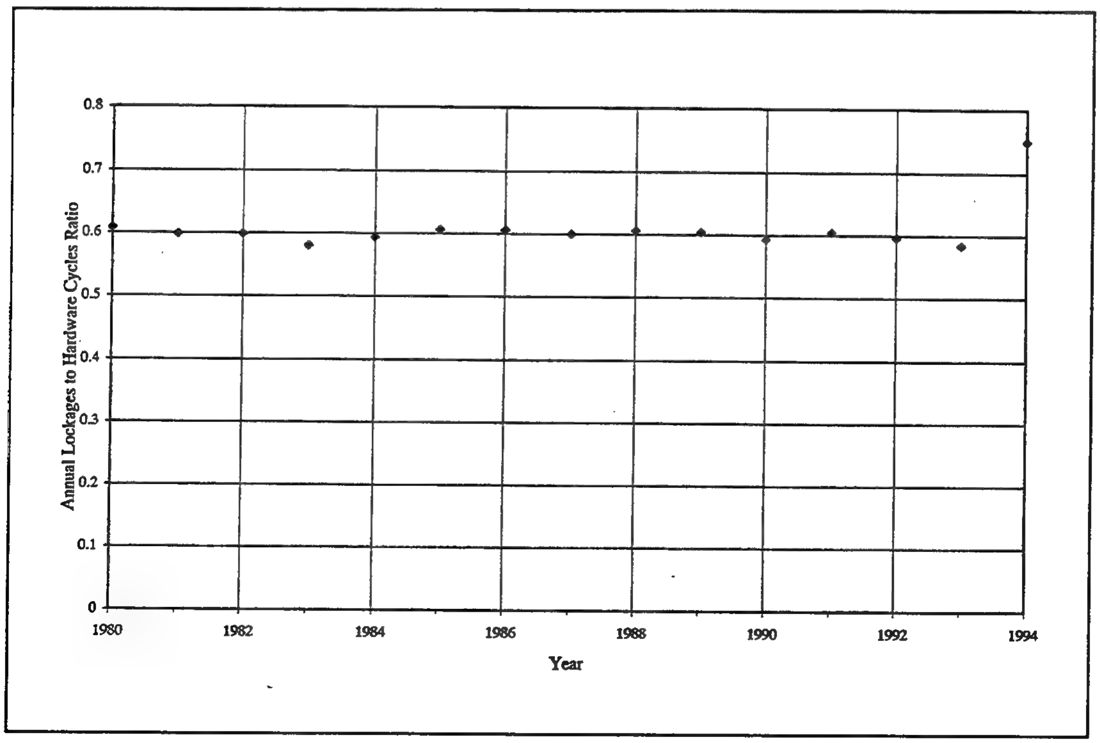


Figure 23. Trend of the ratio of lockages to hardware cycles for Lock and Dam 24

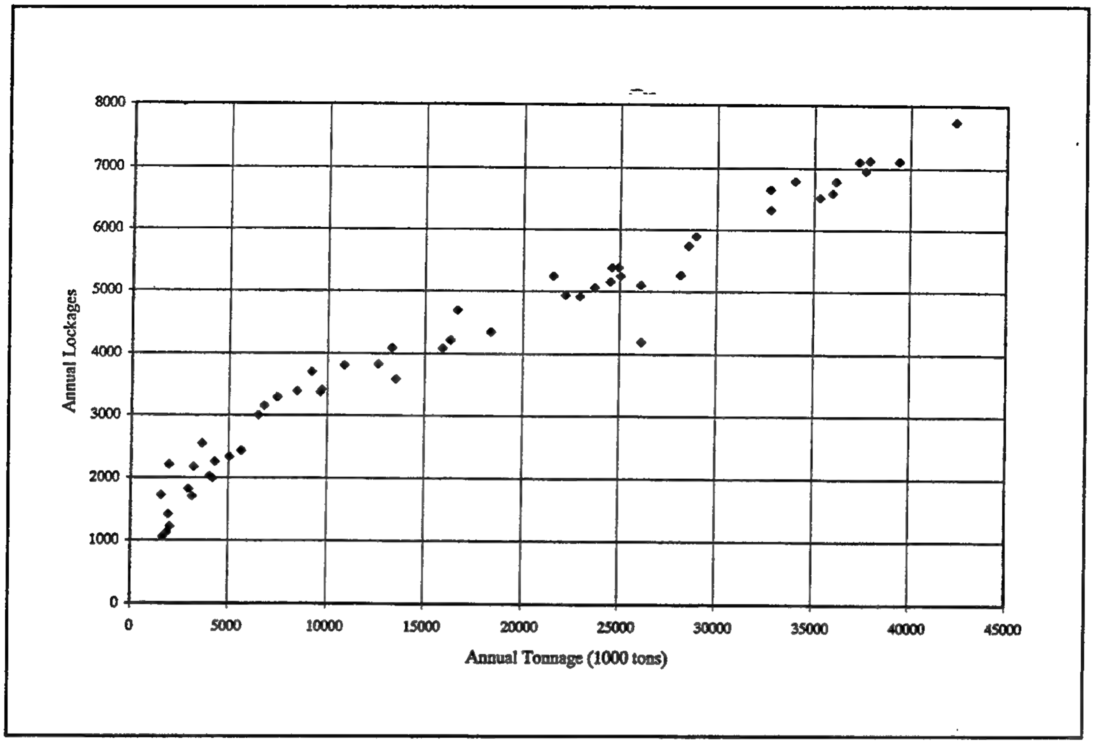


Figure 24. Tonnage and lockages from 1940 to 1994 - Lock and Dam 24

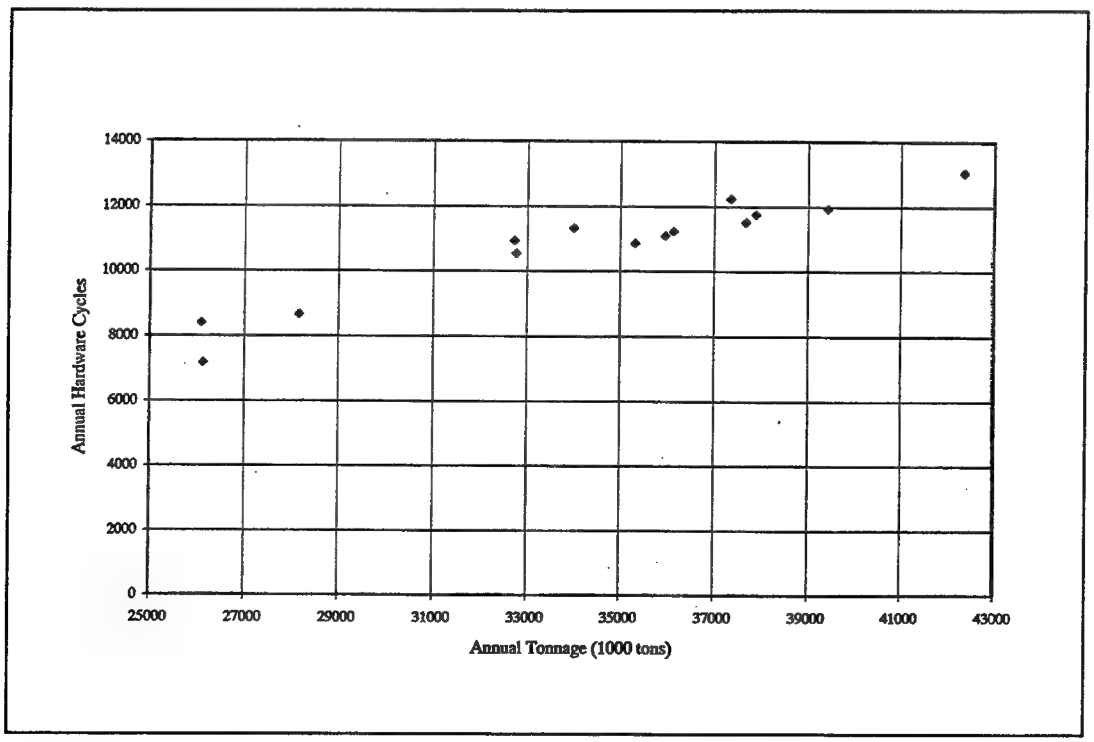


Figure 25. Tonnage and hardware cycles from 1980 to 1994 - Lock and Dam 24

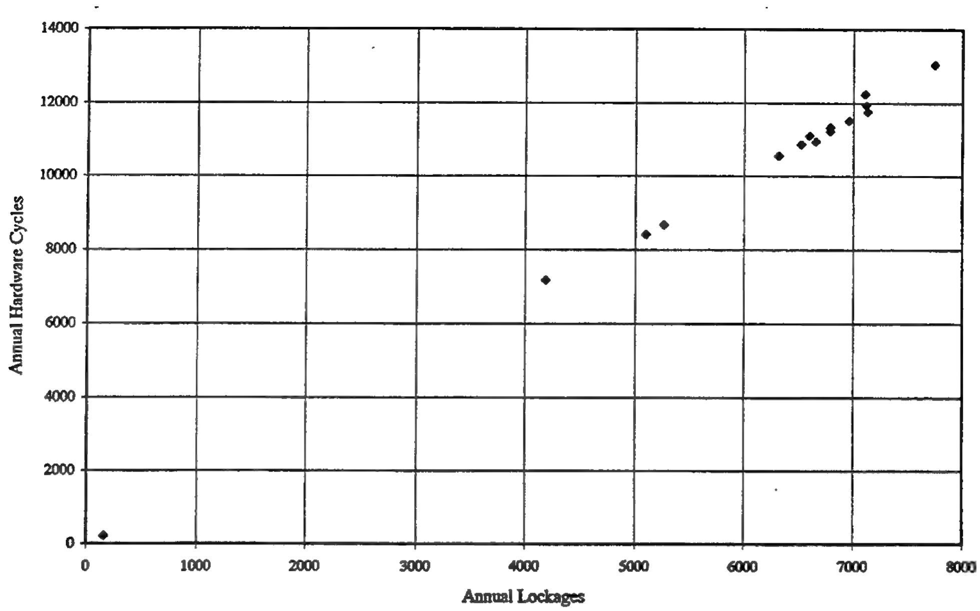


Figure 26. Lockages and hardware cycles from 1980 to 1994 - Lock and Dam 24

Hardware cycles as a function of lockages

According to Equation 36b, a regression model was developed for the relationship between the annual hardware cycles and the annual lockages using the data from the LPMS given in Tables 6 and 7. According to Equations 37 to 40, the model can be expressed as

$$\overline{N}_{HC} = (1.678977 \pm 0.0213)\, N_{loc} - (0)N_{loc}^2 + (-55.1587 \pm 134.07) \qquad (58)$$

Based on the data used in this analysis, only the coefficient *A* is significant, and should be kept in the model. However, both *A* and *C* are used herein. The developed model is of an adequate precision level for all practical purposes, since the standard error of estimates is 148.85 for a sample size of 15 annual values. The results and observations provided herein are lock-specific. For data obtained from other locks, with different patterns of traffic, the significance of the coefficients *A*, *B*, and *C* can be different. The model of Equation 58 and the data are shown in Figure 1.

Trend analysis of annual number of lockages

The trend of the annual number of lockages can be assumed to follow a Poisson distribution with a time variant mean as given by Equation 41. The coefficients of the model , i.e., N_0, A, B, and C, need to be estimated on the basis of curve fitting of the data (Cox and Lewis 1966). The resulting model was obtained in Equations 42 to 45 to be

$$N_{loc}(t) = (1306.66 \pm 1.06)\exp\left((0.050249 \pm 0.003411)t + (-7.4844 \pm 1.2260)x10^{-6}\, t^3\right) \quad (59)$$

where t is the time in years counted from a specified year (for example, 1940 for Lock and Dam 24). Thus, $t = 0$ for 1940, $t = 1$ for 1941, and so on. The significance of the coefficients was estimated using a Stepwise Regression procedure. The correlation coefficient for the model is 0.955. The corresponding standard error is 283.1. The observed, fitted (or predicted using the model) values of annual number of lockages are given in Table 3. The results are also shown in Figure 2. The details for the development of this model are given in Equations 42 through 45.

Number of lockages as a function of tonnage

For cases where data on the annual number of lockages are absent but the annual tonnage data are available, the relationship between annual number of lockages and tonnage can be useful to estimate the number of lockages described in Equation 54. The model development requires the values of annual number of lockages, and the corresponding annual tonnage values. This model does not explicitly account for recreational boats which do not have tonnage values. Therefore, the 4annual number of lockages N_{loc} can be related to annual tonnage T_n (in kilotons) for Lock and Dam 24 for the period 1940 to 1993 as

$$N_{loc} = (0.1432648 \pm 0.00424)T_n + (1682.60 \pm 92.13) \quad (60)$$

where the constant in Equation 60 can be associated with recreational-boat lockages, or with passing ice or debris. The standard error of estimates for this model is 395.96 for a sample of size 54 annual values. The correlation coefficient between annual tonnage and number of lockages is 0.978. The model of Equation 60 and the data are shown in Figure 27.

Tonnage forecast using the GEM

The GEM was used to obtain tonnage forecasts for Lock and Dam 24 for the years 2000, 2010, 2020, 2030, 2040, and 2050. The GEM results consist of low,

medium, and high forecasts. Table 9 shows the GEM forecasts for Lock and Dam 24. The relationship of annual lockages as a function of the annual tonnage (Equation 60) was used to obtain annual lockages for Lock and Dam 24 as shown in Table 9. Then the annual hardware cycles as a function of lockages (Equation 58) were used to obtain the annual hardware cycles for Lock and Dam 24 as shown in Table 10. The forecasts of annual tonnage, lockages, and hardware cycles are shown in Figures 28, 29, 30, respectively.

The GEM tonnage forecast was developed in 1987 for the years 2000, 2010, 2020, 2030, 2040, and 2050. Comparing these forecast values with recently reported "real" values as given in Figure 18 shows clearly that the GEM tonnage forecast has actually underestimated tonnage. An assessment of this type needs to be used to evaluate and possibly revise the GEM.

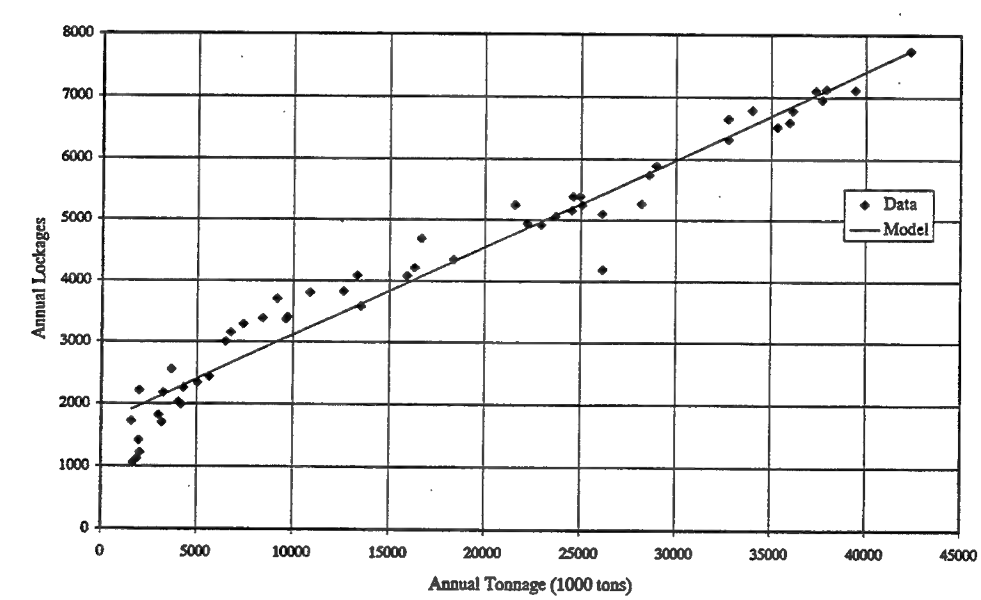


Figure 27. Tonnage and lockages from 1940 to 1994 with regression model - Lock and Dam 24

Table 9
GEM Forecasts of Tonnage and Computed Lockages for Lock and Dam 24

	Tonnage (1000 tons)			Number of Lockages		
Year	High	Medium	Low	High	Medium	Low
2000	41362	41277	41018	7609	7597	7560
2010	41550	41496	41343	7636	7628	7607
2020	41593	41548	41503	7642	7635	7629
2030	41622	41580	41542	7646	7640	7635
2040	41631	41607	41568	7647	7644	7638
2050	41633	41619	41595	7648	7646	7642

Table 10
GEM Forecasts of Tonnage and Computed Hardware Cycles for Lock and Dam 24

	Tonnage (1000 tons)			Number of Hardware Cycles		
Year	High	Medium	Low	High	Medium	Low
2000	41362	41277	41018	12775	12755	12692
2010	41550	41496	41343	12820	12807	12770
2020	41593	41548	41503	12831	12820	12809
2030	41622	41580	41542	12838	12827	12818
2040	41631	41607	41568	12840	12834	12825
2050	41633	41619	41595	12840	12837	12831

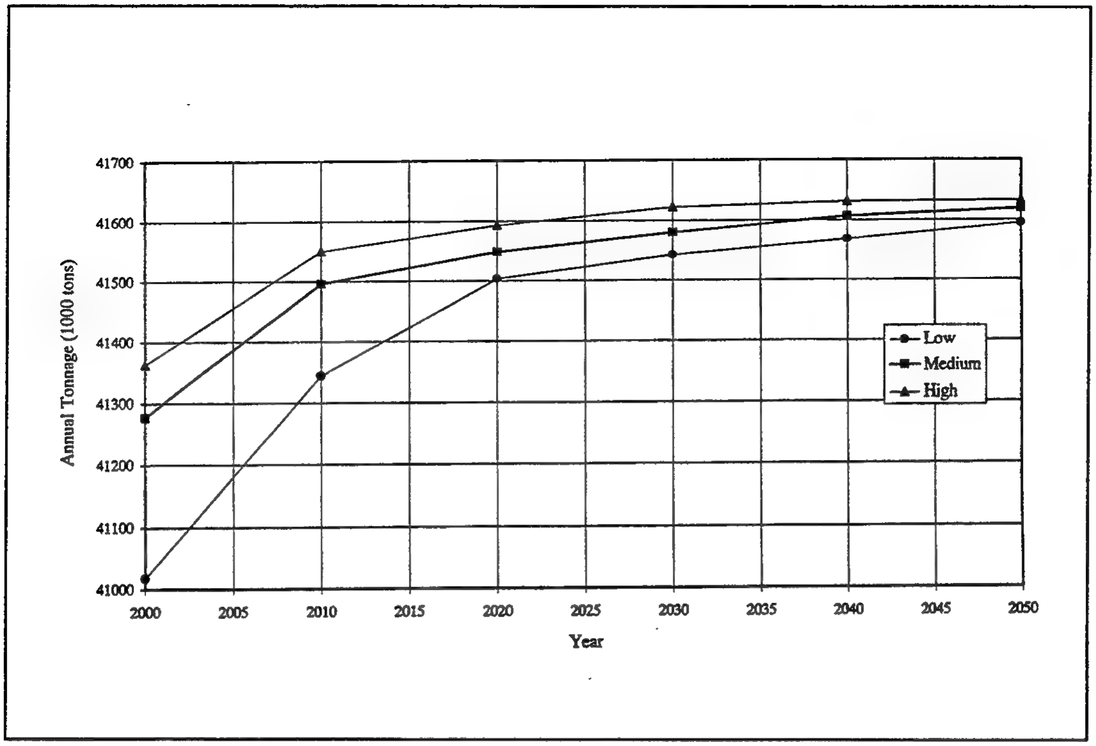


Figure 28. Forecast of annual tonnage for Lock and Dam 24

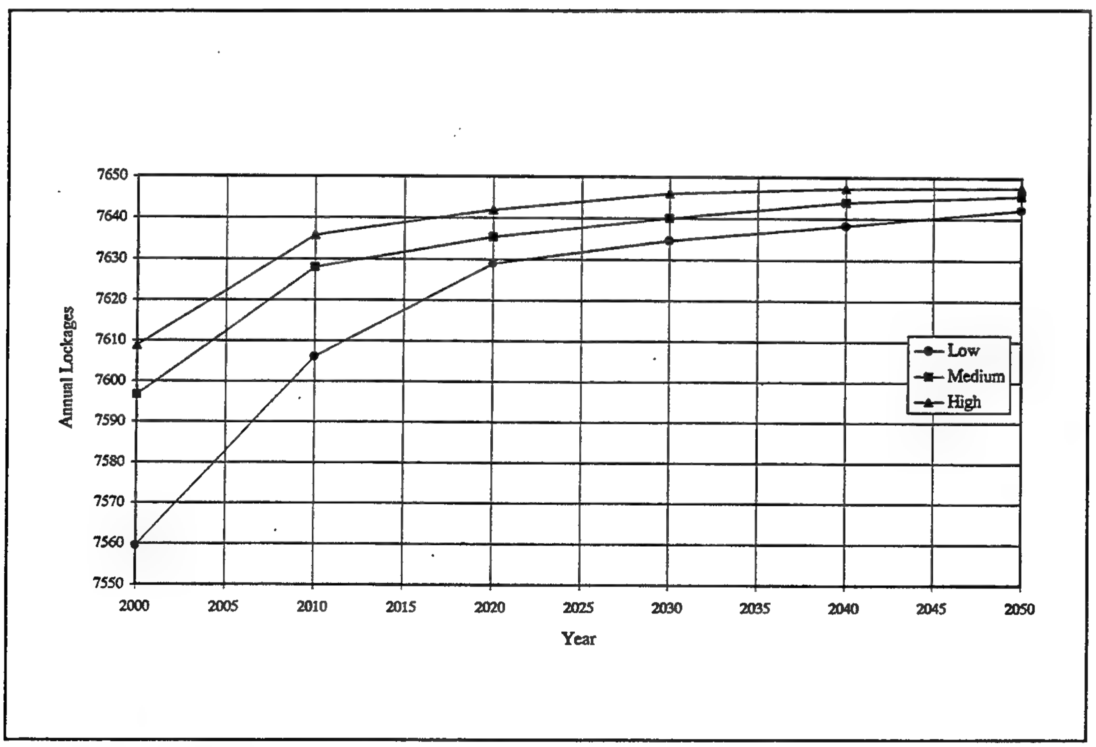


Figure 29. Forecast of annual lockages for Lock and Dam 24

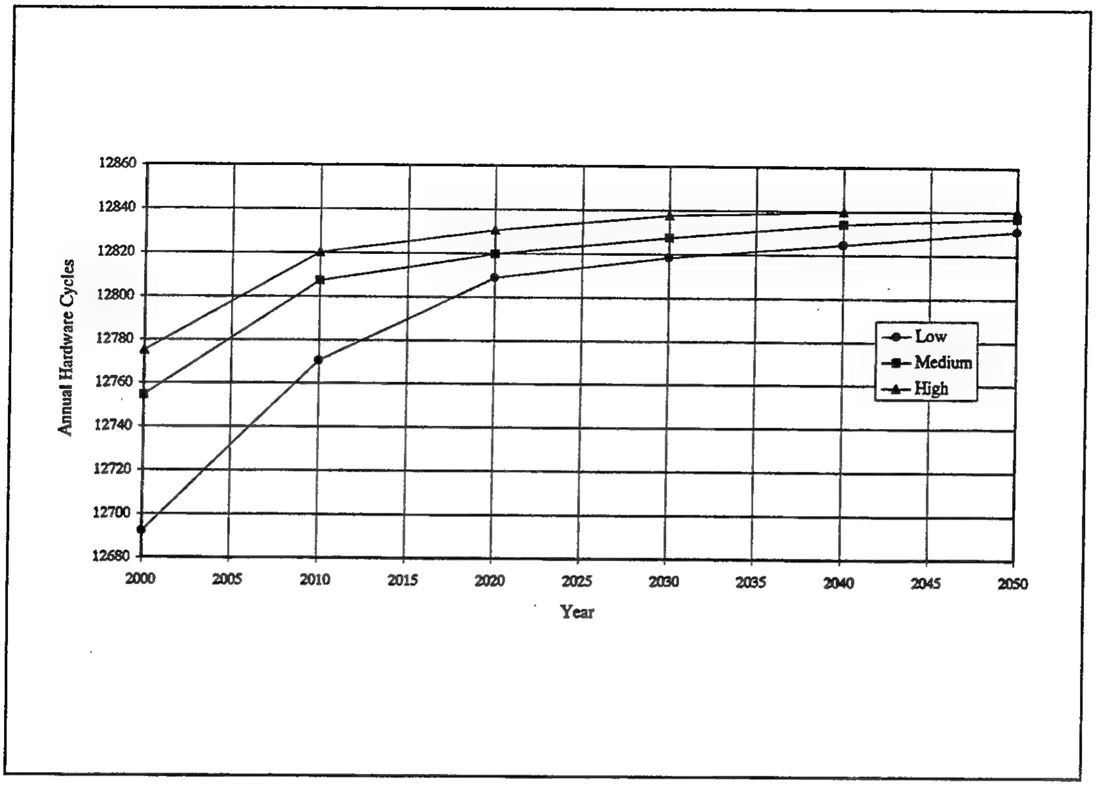


Figure 30. Forecast of annual hardware cycles for Lock and Dam 24

Impact of Results on Fatigue Reliability Assessment

The impact of the results of this study on fatigue reliability assessment was investigated in two forms, (a) its impact on a computed water-head differential (H_d), and (b) its impact on a computed reliability index (β). The former impact assessment is more accurate than the latter one due to approximations employed in the latter assessment. The results reported below can be considered as a preliminary assessment of the effect of the computed water-elevation and hardware cycles on fatigue reliability. A complete assessment of this impact is recommended for a future study.

Impact on water-head differential

The daily water elevation records were used to compute water-head differential (H_d), for which a histogram was developed without regard to load cycles as shown

in Figure 31. The mean head differential is 8.267 ft; the standard deviation is 4.7636 ft; the coefficient of variation is 0.576; and the standard error for the mean is 0.0565 ft. By accounting for the hardware cycles, the histogram was re-evaluated based on Figure 16 and Equation 56b as shown in Figure 32. The weighted mean and standard deviation of the water-head differential based on the hardware cycles are 7.624 ft and 4.937 ft, respectively. The coefficient of variation in this case is 0.647. A USACE study (USAEWES 1994) provided estimates of mean and standard deviation for water-head differential for Lock and Dam 24 of 9.600 ft, and 4.167 ft, respectively. These estimates show that a more rigorous computation of the water-head differential can produce a lower level of head differential due to the effect of hardware cycles.

Impact on reliability index

The statistics of water-head differential were used in the USACE procedure for computing fatigue reliability of a vertical beam for Lock and Dam 24 as described in USACE (1994). The results are shown in Table 11 that demonstrate the effect of water-head differential on the estimated reliability index. The results are approximate since only the mean and standard deviation, not the complete probabilistic characteristics that are available, of the water-head differential were used.

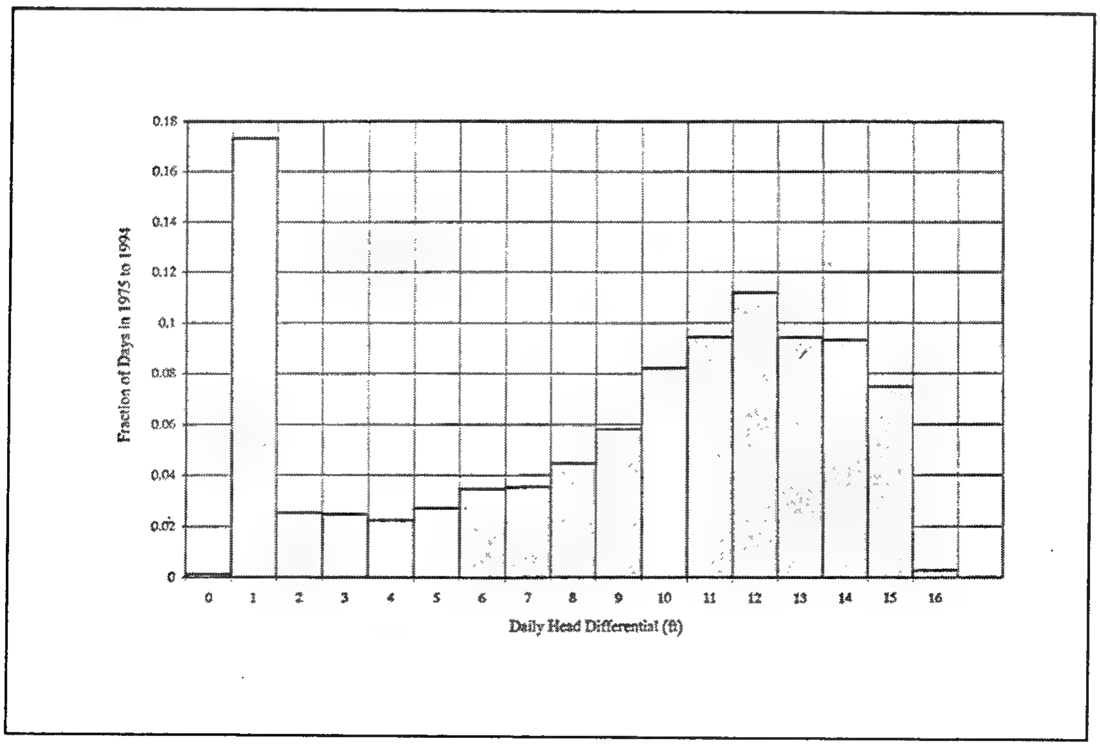


Figure 31. Fraction of days for water-head differential from 1975 to 1994 - Lock and Dam 24

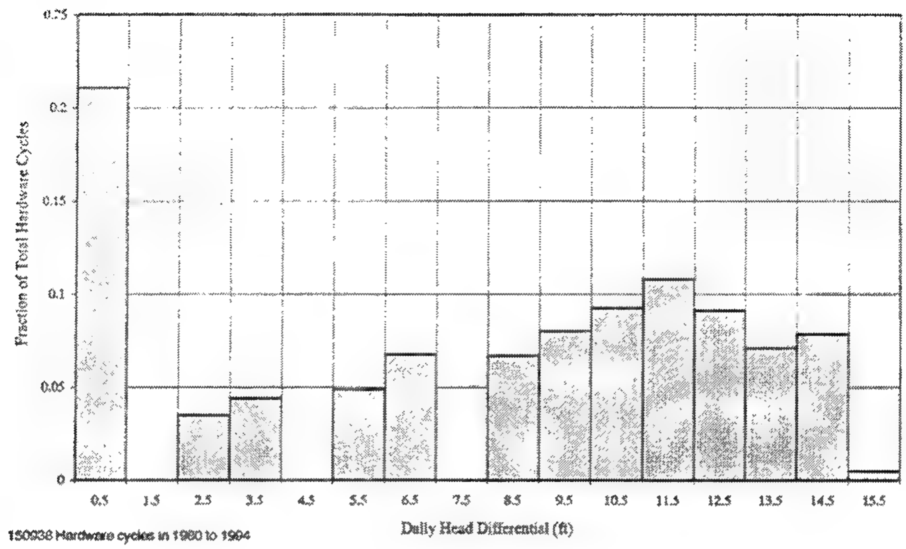


Figure 32. Fraction of total hardware cycles for water-head differential for 1980 to 1994 - Lock and Dam 24

Table 11
Impact of Water-Head Differential on Fatigue Reliability

	Water-Head Differential			
Method	**Mean (ft)**	**Standard Deviation (ft)**	**Coefficient of Variation**	**Estimated Reliability Index**
USACE (1994)	9.600	4.167	0.434	2.6
Water head only	8.267	4.764	0.576	2.9
Water head and hardware cycles	7.624	4.937	0.648	3.1

6 Recommendations

As a result of using the LPMS, the development of the probabilistic model, and performing the analysis, several recommendations are given below.

The LPMS entries were used in this study to compute hardware cycles that are needed for fatigue-reliability evaluation. However, the computations of hardware cycles require a significant level of effort. The computation of hardware cycles can be facilitated by adding a field to the LPMS to keep track of these hardware cycles, associate times, and pool and tailwater elevations. Counting hardware devices with timers and pressure sensors can be developed to perform this function. Alternatively, current fields of the LPMS can be improved to facilitate the computations of hardware cycles. Also, the following observations are provided as suggestions for the LPMS:

a. The current entry and exit types in the LPMS do not necessarily reflect the turnback type if it was delayed, i.e., not immediate to an entry or exit, respectively. Depending on the use of these fields in their current forms, either new fields should be developed that correct for the delayed turnback occurrence, or the current fields should be revised.

b. The fields of the LPMS need to be logically connected in order to prevent erroneous entries.

c. Sometimes several vessel records were entered in the LPMS as separate lockages, but these vessels were serviced in the same operation of opening and closing of miter gates. The LPMS does not keep track of these cases, thereby complicating the computation of hardware cycles.

d. Ice and debris lockages are not included in the LPMS. The practice of record keeping needs to be revised to require the inclusion of these lockages.

e. Other operations of the gates for service, inspection, or performance evaluations are not recorded in the LPMS. A similar action to item *d* is recommended for these operations.

In general, locks and dams on the Mississippi River can be classified into groups. A typical lock can be analyzed from each group, in addition to analyzing several locks in a selected group, to produce a complete understanding of

hardware cycles of miter gates. Relationships and variability among the groups and within a group can then be studied and understood.

The GEM tonnage forecast was developed in 1987 for the years 2000, 2010, 2020, 2030, 2040, and 2050. Comparing these forecast values with recently reported "real" values shows clearly that the GEM tonnage forecast has actually underestimated tonnage. An assessment of this type needs to be used to evaluate and possibly revise the GEM. Studies in this area are needed and recommended.

This study includes a preliminary assessment of the effect of the computed water-elevation and hardware cycles on fatigue reliability. A complete assessment of this impact is recommended for a future study.

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Appendix A

Daily Hardware Cycles for Lock and Dam 24

Day	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994
1	15	5	4	17	4	4	6	15	6	4	1	1		4	1
2	5	1	16	4	7	5	1	16	3	8	2	8		7	1
3	1	12	24	10	1	1	1	2	4	4	3	3		3	1
4	9	4	2	11	15	3	4	9	6	1	5	2		17	4
5	18	1	2	13	4	4	4	1	3	2	1	4		5	7
6	7	1	9	1	1	9	1	10	6	2	4	1		4	7
7	12	10	10	12	1	2	8	5	7	2	1	1		14	6
8	4	8	1	12	2	2	5	4	1	1	5	6		7	7
9	5	2	12	3	3	9	2	1	1	1	7	7		6	1
10	5	3	3	9	9	1	2	6	1	1	8	3		9	6
11	2	3	1	5	5	7	9	8	8	2	13	3		8	1
12	6	3	9	15	4	1	4	1	1	2	4	4		6	3
13	1	8	1	2	2	1	7	3	1	3	16	2		6	1
14	4	1	4	8	6	1	7	4	1	1	4	2		4	1
15	1	7	1	8	10	14	7	7	1	1	12	7		14	1
16	12	4	4	6	3	1	5	6	1	1	8	4		2	2
17	3	11	1	6	4	1	6	5	8	1	6	8		5	1
18	5	6	10	10	1	5	6	1	1	2	2	5		4	4
19	5	7	3	5	9	4	3	1	8	2	4	8		1	7
20	13	7	1	7	8	1	6	1	1	1	7	7		5	1
21	5	6	4	9	1	1	5	8	3	3	6	4		7	4
22	3	4	7	5	1	1	4	2	9	1	4	4		8	1
23	2	9	1	4	5	1	11	8	8	1	11	6		2	1
24	7	12	1	1	4	1	6	8	3	1	1	3		8	2
25	9	1	6	15	1	1	9	1	18	3	10	8		6	1
26	7	5	5	2	6	14	4	1	1	1	1	5		10	4
27	4	4	8	9	3	1	1	4	1	1	3	1		3	2
28	1	4	1	11	4	1	3	1	1	4	12	2		1	1
29	3	4	5	11	4	1	3	1	1	3	6	6		5	4
30	4	3	5	2	4	1	1	4	7	2	19	3		4	4
31	1	5	4	1	1	10	5	1	7	1	5	5		4	4
32	6	5	1	8	1	1	5	6	6	2	8	7		8	13
33	1	8	1	1	5	1	2	4	3	2	10	5		4	8
34	1	3	5	8	6	1	3	1	8	3	5	3		2	5
35	1	5	1	1	12	1	1	4	1	2	15	2		2	4
36	1	1	1	4	6	3	7	4	1	2	22	3		4	1
37	4	4	1	5	4	8	1	5	1	1	9	3		1	2
38	1	8	1	1	12	13	4	12	3	1	7	2		7	2
39	8	7	1	3	4	4	10	2	11	1	9	5		4	2
40	2	1	1	4	8	2	4	1	1	1	1	4		10	6
41	3	1	1	10	4	6	2	1	1	3	14	2		4	1
42	7	1	1	4	4	1	7	2	4	4	8	5		6	3
43	14	3	9	1	2	1	2	9	1	2	14	8		6	4
44	3	2	4	5	5	3	1	4	1	1	4	7		10	5
45	7	1	1	11	12	2	1	8	1	1	3	3		11	3
46	1	1	8	7	7	3	1	4	8	1	2	4		8	2
47	1	1	1	11	6	2	2	10	1	1	12	5		1	1

Day	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994
48	5	1	1	5	15	1	1	5	1	3	3	2		4	1
49	3	1	1	8	10	2	2	4	6	1	12	8		9	1
50	6	1	1	3	23	4	4	8	5	3	17	7		4	10
51	4	4	1	5	20	2	5	10	2	1	14	8		10	6
52	2	4	1	10	24	3	2	2	3	1	22	14		5	4
53	2	1	3	5	49	1	6	4	3	1	13	6		1	4
54	3	6	5	1	55	1	8	3	8	1	14	7		4	5
55	2	10	6	11	44	2	3	2	11	3	11	11		9	11
56	4	1	5	16	27	1	6	6	5	4	28	8		1	4
57	1	27	6	16	20	6	2	11	7	2	16	5		1	4
58	1	23	8	23	4	2	14	3	9	1	22	14		2	5
59	1	22	21	14	39	9	10	4	11	5	36	14		8	11
60	1	18	0	10	36	12	9	4	1	0	34	12	9	7	
61	0	16	7	19	45	12	4	6	10	1	26	24	54	8	
62	0	24	7	43	21	4	9	13	8	3	24	26	60	5	
63	0	15	14	9	22	15	6	11	19	11	24	20	51	12	
64	0	25	2	25	20	4	10	28	32	4	35	14	18	24	
65	0	35	23	22	30	5	9	20	21	2	23	22	27	23	
66	7	25	16	30	32	8	11	15	25	14	35	22	40	20	
67	0	25	5	26	34	4	9	20	27	22	34	32	38	23	
68	1	31	24	23	34	22	13	30	28	19	41	39	52	22	
69	3	30	9	20	39	36	12	24	32	31	39	37	47	36	
70	12	26	16	27	34	20	18	17	31	22	35	30	30	30	
71	3	32	5	20	45	23	31	24	9	32	46	43	7	24	
72	4	31	18	22	16	27	13	22	29	29	39	29	51	26	
73	20	42	23	19	51	12	20	33	28	26	41	28	30	16	
74	16	22	30	47	23	28	24	23	13	33	39	23	31	39	
75	36	43	23	31	27	32	19	33	41	30	37	41	39	36	
76	15	30	21	38	30	44	38	31	29	38	46	27	43	30	
77	20	38	27	32	37	50	23	25	46	21	30	38	42	41	
78	31	27	14	33	32	42	28	17	25	40	42	34	31	19	
79	30	26	14	38	47	30	17	32	43	31	38	23	28	26	
80	24	44	48	16	23	31	33	34	33	35	45	36	42	38	
81	48	31	41	26	38	31	35	38	44	28	54	53	51	26	
82	32	39	35	14	24	24	17	36	43	38	58	43	42	41	
83	29	33	37	21	43	29	19	28	45	27	44	48	60	34	
84	43	38	46	27	47	37	23	30	39	42	50	50	48	24	
85	24	41	23	34	39	26	23	34	33	45	49	32	27	28	
86	28	37	40	29	32	22	39	31	28	41	37	28	39	27	
87	38	24	52	38	31	30	23	35	41	24	52	10	42	35	
88	36	45	37	34	41	15	27	31	52	35	22	38	33	20	
89	34	46	28	19	41	27	28	31	34	32	42	32	42	39	
90	27	29	26	43	32	38	43	20	38	32	20	36	46	40	
91	24	21	31	34	42	36	30	28	44	42	37	50	45	39	
92	40	35	27	46	40	26	27	33	46	57	43	37	54	34	
93	29	46	25	26	53	26	52	25	39	31	48	32	46	39	
94	29	44	23	0	42	26	32	31	35	42	48	33	43	34	

Day	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994
95	26	35	35	0	38	26	28	25	46	38	39	30	43	45	
96	37	52	44	0	48	15	34	39	36	38	40	41	40	37	
97	39	35	31	0	59	38	34	37	36	38	42	34	43	28	
98	37	37	31	0	45	44	44	27	46	36	39	42	38	20	
99	28	46	33	6	48	41	38	39	37	31	47	45	48	20	
100	19	44	46	4	47	37	30	27	47	53	48	49	44	19	
101	41	43	38	0	47	41	27	36	34	29	41	40	49	20	
102	32	38	45	0	47	39	9	43	43	40	41	37	53	18	
103	44	43	27	54	39	37	17	40	44	46	46	27	57	34	
104	34	39	47	49	40	29	10	42	42	35	44	40	42	34	
105	17	32	33	66	52	28	12	23	45	36	31	35	48	57	
106	28	36	37	58	51	36	10	31	43	43	23	42	44	46	
107	53	42	19	56	50	18	8	33	48	43	46	35	31	22	
108	48	39	31	40	43	36	6	29	50	37	45	55	40	39	
109	42	34	57	44	41	48	16	44	45	49	43	46	47	47	
110	29	56	41	35	35	32	28	40	53	50	56	42	37	38	
111	40	50	40	52	50	44	42	41	43	46	34	36	43	5	
112	49	44	39	44	35	34	40	27	45	32	37	40	46	0	
113	26	26	37	27	45	26	35	23	43	35	48	50	43	0	
114	32	44	54	22	42	26	40	42	43	42	52	46	50	0	
115	44	49	50	49	49	38	28	41	46	37	52	47	61	0	
116	27	49	25	44	59	34	26	35	39	47	51	48	41	0	
117	31	37	63	34	47	44	22	37	43	31	52	51	45	0	
118	39	49	40	33	34	30	35	19	44	47	53	51	49	0	
119	13	41	38	32	48	33	34	41	43	43	58	59	34	0	
120	41	31	35	38	32	40	36	37	44	49	51	56	46	0	
121	29	40	40	52	40	37	35	48	45	51	46	45	42	0	
122	32	41	37	41	44	31	38	31	38	42	44	32	52	0	
123	29	38	47	33	34	21	32	41	47	41	53	43	51	14	
124	36	42	45	44	23	32	16	41	36	40	51	25	41	26	
125	24	46	39	30	32	25	47	28	41	50	56	49	52	12	
126	33	48	45	31	13	31	34	34	40	46	47	50	48	0	
127	37	42	34	36	56	41	33	37	51	49	53	42	26	0	
128	23	28	53	49	50	25	37	34	50	43	54	53	33	0	
129	21	47	47	20	51	25	36	43	44	42	54	34	47	0	
130	24	18	43	35	36	34	48	48	40	47	47	45	45	16	
131	25	42	38	26	43	29	23	30	44	44	52	41	55	21	
132	32	42	33	40	44	35	22	28	44	35	54	24	37	59	
133	34	37	49	31	42	29	28	47	46	40	51	35	52	44	
134	14	42	44	37	51	24	17	44	44	38	56	47	27	45	
135	32	42	33	46	43	23	21	34	45	33	64	43	40	57	
136	40	40	36	26	48	26	41	35	57	31	45	33	53	61	
137	32	41	59	28	24	32	26	33	47	42	59	43	54	59	
138	32	38	39	42	38	31	30	44	43	37	44	45	56	62	
139	25	42	46	39	34	21	8	43	40	45	50	59	46	63	
140	37	32	45	48	34	30	21	49	36	48	36	51	44	62	
141	32	32	40	50	43	29	10	42	47	45	43	25	44	61	

Day	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994
142	33	33	59	45	28	17	10	39	48	45	52	37	44	35	
143	31	29	54	34	38	35	25	45	46	35	46	37	35	47	
144	35	42	43	46	29	32	41	55	50	41	47	56	47	57	
145	36	41	37	24	43	42	19	36	42	47	53	43	50	61	
146	42	44	36	48	22	34	29	48	58	41	61	41	49	35	
147	42	39	40	32	45	41	26	49	47	40	43	46	54	45	
148	41	48	42	34	27	29	38	30	50	38	23	43	47	32	
149	28	40	46	47	49	15	33	45	49	53	48	24	51	41	
150	42	44	52	54	48	24	28	49	43	42	59	40	46	60	
151	44	40	46	43	37	21	30	41	49	38	54	33	46	47	
152	35	51	49	46	31	42	32	28	43	45	68	42	48	54	
153	34	35	49	41	38	20	19	23	40	38	62	41	45	50	
154	28	41	48	31	39	15	14	37	32	41	55	44	46	60	
155	37	44	51	42	51	28	28	34	40	38	52	33	43	49	
156	37	27	49	44	33	31	12	33	49	42	53	29	50	47	
157	32	43	35	54	29	37	31	50	50	50	61	55	44	38	
158	34	49	56	45	45	25	36	43	35	50	57	54	50	53	
159	26	38	57	39	7	20	29	40	41	45	42	55	53	41	
160	44	25	35	29	40	29	31	48	35	45	54	36	50	49	
161	52	43	34	37	58	18	38	47	38	51	58	29	49	39	
162	36	43	52	36	29	23	19	38	41	34	47	34	35	36	
163	32	39	54	42	45	23	29	45	56	48	49	35	39	41	
164	26	34	55	32	23	21	44	52	33	46	51	46	24	53	
165	41	47	43	37	33	24	16	45	40	38	60	37	40	41	
166	31	43	52	31	39	36	39	41	50	39	40	34	43	33	
167	44	45	39	46	28	27	14	34	29	41	35	51	45	45	
168	35	45	39	46	51	27	24	39	43	41	60	42	47	43	
169	27	38	41	41	36	21	29	40	34	44	50	47	47	47	
170	35	29	31	51	32	43	28	25	40	45	42	41	52	56	
171	42	42	45	50	34	25	22	29	44	44	52	37	51	48	
172	30	39	29	44	47	39	25	33	40	48	47	44	52	34	
173	48	42	52	49	18	25	46	42	42	49	32	29	52	47	
174	44	35	28	49	27	20	24	31	40	40	24	45	56	22	
175	38	39	30	36	37	37	34	40	24	52	3	36	46	33	
176	34	26	26	48	21	31	34	30	39	44	34	40	44	36	
177	40	51	39	45	33	35	50	33	55	43	34	47	44	17	
178	35	26	35	32	48	27	25	41	44	46	46	35	41	8	
179	51	42	30	46	38	31	47	37	24	50	48	55	46	0	
180	37	36	24	36	28	24	41	45	32	44	37	37	48	0	
181	46	20	15	47	38	35	39	21	34	49	62	43	52	0	
182	39	30	19	41	32	43	34	44	31	54	58	51	49		
183	34	27	47	52	42	34	26	41	41	50	55	59	52		
184	42	28	60	56	30	28	25	45	31	48	57	53	58		
185	41	29	50	44	48	37	49	50	47	54	61	48	54		
186	49	39	46	45	37	33	49	54	54	51	60	51	53		
187	42	22	18	41	44	41	40	31	43	55	54	44	51		
188	44	22	36	43	36	50	33	43	38	53	62	53	50		

Day	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994
189	48	23	32	58	34	21	29	43	27	44	45	45	55		
190	29	49	31	48	25	27	31	31	42	53	62	43	46		
191	40	48	36	53	36	39	28	42	31	51	45	41	53		
192	42	48	36	36	27	34	31	44	37	43	52	36	49		
193	33	40	30	43	14	43	27	40	26	51	46	56	52		
194	36	39	25	44	43	32	24	44	39	41	43	51	54		
195	44	33	25	39	42	21	23	38	41	42	51	47	52		
196	41	26	44	39	37	42	28	49	23	34	51	36	56		
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366	11				5				4				13		

Appendix B

Notation

a	Parameter of the Weibull distribution
α_i	Monthly fraction of upstream traffic
A	Regression coefficient
α	Fraction of traffic moving upstream
b	Parameter of the Weibull distribution
B	Regression coefficient
β	Reliability index
β_i	Fraction of vessels in a month from the traffic of a year
C	Regression coefficient
CNC	Corrected number of lockage cuts
DR	Direction of lockage (up or down)
DY	Day of shift
ΔN_{HC}	Decrease in the mean of total hardware cycles due to simultaneously servicing multiple boats
δt	Average service time in the lock for a vessel
δt_d	Service time in the lock for a vessel in downstream traffic
δt_u	Service time in the lock for a vessel in the upstream traffic
EOL1	End of lockage time (24 hr) first cut
EOL2	End of lockage time (24 hr) last cut
ET	Entry type
$f_L(l)$	Probability density function of vessel length L
$F_L(l)$	Cumulative distribution function of length of the vessel population
GEM	General Equilibrium Model
HC	Number of hardware cycles
h_t	Tailwater elevation value
H_d	Water-head differential
H_p	Pool elevation (or height) of water
H_{pn}	Normalized pool elevation (or height) of water
H_t	Tailwater elevation (or height)
H_{tn}	Normalized tailwater elevation (or height)
H_{tmax}	Maximum tailwater elevation (or height)

H_{tmin}	Minimum tailwater elevation (or height)
H_p	Predicted value of H_p
k	Number of cuts
K	Coefficient for expressing seasonal variation in traffic volume and direction
K_c	Mean hardware cycles per lockage
l_{max}	Maximum length of a vessel which can be locked in one operation of a lock
LG	Number of lockages
LN	Lock number
LPMS	Lock Performance Monitoring System
LT	Lockage type
λ	Rate of vessel arrival at a lock
λ_d	Poisson arrival rate to a lock of vessels for downstream traffic
λ_u	Poisson arrival rate to a lock of vessels for upstream traffic
MO	Month of shift
N_0	Model coefficient
N_1	Number of vessels which are not cut
N_2	Number of vessels which are cut into two parts
NC	Number of lockage cuts
N_{cuts}	Number of cuts
N_{HC}	Total number of hardware cycles
N_{HCi}	Number of hardware cycles for i cuts
N_k	Number of vessels which are cut into k parts
NL	Number of discrete vessel lengths
N_{loc}	Number of lockages
N_v	Number of vessels arriving at a lock in time T
$\overline{N}_v$	Mean number of vessels arriving in time T
N_{vd}	Mean number of vessels arriving at a lock in time T from upstream direction
N_{vi}	Number of vessels in the ith month for $i = 1, 2, \ldots, 12$
N_{vu}	Mean number of vessels arriving at a lock in time T from downstream direction
$\overline{N}_1$	Mean number of vessels which are not cut
$\overline{N}_2$	Mean number of vessels which are cut into two parts
$\overline{N}_k$	Mean number of vessels which are cut into k parts;
$\overline{N}_{HC}$	Mean of total number of hardware cycles
$\overline{N}_{HCi}$	Mean number of hardware cycles for i cuts
ΔN_{HCd}	Mean decrease in the number of hardware cycles in the downstream traffic

ΔN_{HCu}	Mean decrease in the number of hardware cycles in the upstream traffic
ΔN_{HCt}	Mean decrease in the number of hardware cycles for two-direction traffic
$p_L(l_i)$	Probability mass value of a vessel length L
p_s	Probability that a given boat is being serviced simultaneously with other boats
P_1	Probability that a vessel is not being cut
P_2	Probability that a vessel is being cut into two parts
P_k	Probability that a vessel is being cut into k parts
SOL1	Start of lockage time (24 hr) 1st cut
t	Time in years
T	Reference time period
T_i	Monthly reference time period for $i = 1, 2, ..., 12$;
TN	Tonnage
T_n	Annual tonnage
$\overline{T}_n$	Mean annual tonnage
$\overline{T}_0$	Model coefficient for mean annual tonnage
$Var(N_1)$	Variance of number of vessels which are not cut
$Var(N_2)$	Variance of number of vessels which are cut into two parts
$Var(N_{HC})$	Variance of total number of hardware cycles
$Var(N_k)$	Variance of number of vessels which are cut into k parts
VT	Vessel type
x, X	Random value or variable
XT	Exit type
YR	Year of shift

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13. ABSTRACT ***(Maximum 200 words)***

Miter gates at navigation locks experience loading cycles from emptying and filling of a lock's chamber as they are opened to allow traffic through the locks. Reliability analysis of miter gates at navigation locks requires definition of (a) nonperformance modes, (b) loads, (c) structural strength, and (d) methods of reliability analysis. Due to the cyclic loading nature of miter gates, the fatigue of critical details requires examination using reliability methods. The assessment of fatigue reliability of these details as a function of time requires the knowledge of strength, stress ranges, and loading cycles for these details.

Prediction of loading cycles on miter gates for use in the assessment of fatigue reliability for miter gates is described. Correlation of field data for pool and tailwater elevations and barge traffic to form a loading histogram to be utilized to better predict the loading history of miter gates is explained.

14. SUBJECT TERMS

Reliability	Lockages	Tailwater
Miter Gates	Locks	Pool water
Fatigue	Hardware Cycles	Loading histogram
Reliability Index		

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